Multiple glow discharges for the excitation of a high power CO2 laser

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MULTIPLE GLOW DISCHARGES FOR THE EXCITATION OF A HIGH POWER CO₂ LASER

by

D R Evans B.Sc., M.Sc., AMIEE

A DOCTORAL THESIS
Submitted in partial fulfilment of the requirements for the award of PhD of the University of Technology, Loughborough 1987.

Supervisor: Dr J E Harry

Department of Electronic and Electrical Engineering

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Multiple glow discharges have been studied and both electrode and aerodynamic techniques investigated to enable operation of a large volume high power glow discharge to excite a high power CO$_2$ laser. A wide range of electrode configurations was investigated and the advantages of using multiple anodes with large surface area multiple cathodes determined. The results were applied to the design of a high flow rate gas recirculating laser to extend the range of aerodynamic investigations to near sonic velocity gas flows in order to study the interaction of turbulent gas flows with the multiple glow discharges. Turbulence within the glow discharge was also generated by using a magnetic field to rotate the discharge at high velocities. The magnetic technique resulted in greatly improved spatial uniformity of the discharge and a six-fold increase in discharge power.

The work led to the use of a novel method of injecting gas through multiple anodes to uniformly distribute the discharge in an axially symmetric turbulent gas flow to stabilise the discharge column. A 5 kW fast axial flow CO$_2$ laser was developed using multiple gas injection electrodes which produced more than three times the power per unit length of discharge and a laser head one fifth the size of any other 5 kW laser reported in the literature.
ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the encouragement and guidance of my supervisor and friend Dr J E Harry throughout this work.

I am grateful to Mr J Wasko and to JEC Lasers Inc. for their considerable financial commitment to the project which made this work possible.

I would like to thank Mr L Monk and Mr G Wagg for their help in constructing equipment.

Finally, my sincere thanks go to my wife, who typed this thesis and who lovingly helped me throughout the work, and also to my family for their understanding and encouragement.
To my wife, Adrienne.
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<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>a</td>
<td>fractional cavity loss</td>
<td>-</td>
</tr>
<tr>
<td>c</td>
<td>velocity of light ( (3 \times 10^8) )</td>
<td>m/s</td>
</tr>
<tr>
<td>f</td>
<td>frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>?</td>
<td>focal length</td>
<td>m</td>
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<tr>
<td>( f_{1,2,3} )</td>
<td>characteristic frequencies</td>
<td>Hz</td>
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<tr>
<td>g</td>
<td>acceleration due to gravity</td>
<td>m/s²</td>
</tr>
<tr>
<td>( g_0 )</td>
<td>unsaturated gain coefficient</td>
<td>-</td>
</tr>
<tr>
<td>h</td>
<td>Planck's constant ( (6.625 \times 10^{-34}) )</td>
<td>J</td>
</tr>
<tr>
<td>?</td>
<td>enthalpy of gas</td>
<td>J</td>
</tr>
<tr>
<td>k</td>
<td>Boltzmann's constant ( (1.38 \times 10^{-23}) )</td>
<td>J/K</td>
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<td>l</td>
<td>mirror separation</td>
<td>m</td>
</tr>
<tr>
<td>?</td>
<td>length of active region</td>
<td>m</td>
</tr>
<tr>
<td>m</td>
<td>mass flow rate</td>
<td>kg/s</td>
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<tr>
<td>n</td>
<td>number of multiple electrodes</td>
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<td>( n_{1,2,3} )</td>
<td>quantum numbers</td>
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</tr>
<tr>
<td>r</td>
<td>radius</td>
<td>m</td>
</tr>
<tr>
<td>( r_{1,2} )</td>
<td>beam radius at mirror surface</td>
<td>m</td>
</tr>
<tr>
<td>t</td>
<td>time</td>
<td>s</td>
</tr>
<tr>
<td>( T )</td>
<td>output coupler transmission</td>
<td>-</td>
</tr>
<tr>
<td>A</td>
<td>area</td>
<td>m²</td>
</tr>
<tr>
<td>B</td>
<td>magnetic flux density</td>
<td>T</td>
</tr>
<tr>
<td>?</td>
<td>rotational constant</td>
<td>-</td>
</tr>
<tr>
<td>( C_p )</td>
<td>specific heat capacity at constant pressure</td>
<td>J/kg/°C</td>
</tr>
<tr>
<td>E</td>
<td>electric field strength</td>
<td>V/m</td>
</tr>
<tr>
<td>( E_{1,2} )</td>
<td>energy emitted from excited state</td>
<td>J</td>
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$E_J$  energy associated with $J$th rotational level  

$F$  force  

$I$  current  

$I_7$  moment of inertia  

$I_{a}$  current at start of abnormal glow  

$I_d$  discharge current  

$I_f$  field current  

$I_i$  current at onset of discharge instability  

$I_0$  output beam intensity  

$I_s$  saturation intensity  

$J$  current density  

$J_a$  cathode current density at start of abnormal glow  

$J_c$  cathode current density  

$J_i$  cathode current density at onset of discharge  

$M$  Mach number  

$N$  neutral particle density  

$'p$  gas pressure  

$P$  power  

$P_e$  electrical power  

$P_g$  thermal power dissipated in gas  

$P_{\text{max}}$  maximum laser output power  

\text{unit}  

$\text{J}$  

$\text{N}$  

$\text{A}$  

$\text{kg.m}^2$  

$\text{W/cm}^2$  

$\text{W/cm}^2$  

$\text{A/m}^2$  

$\text{A/m}^2$  

$\text{A/m}^2$  

$-3$  

$\text{mb}$  

$\text{W}$  

$\text{W}$  

$\text{W}$
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<th>Description</th>
<th>Unit</th>
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<td>$P_0$</td>
<td>laser output power</td>
<td>W</td>
</tr>
<tr>
<td>$P^*$</td>
<td>gas pressure at sonic velocity location</td>
<td>mb</td>
</tr>
<tr>
<td>$P$</td>
<td>differential pressure</td>
<td>mb</td>
</tr>
<tr>
<td>$Q$</td>
<td>energy transfer</td>
<td>J</td>
</tr>
<tr>
<td>$Q_T$</td>
<td>total energy transfer</td>
<td>J</td>
</tr>
<tr>
<td>$R_{1,2}$</td>
<td>mirror radius of curvature</td>
<td>m</td>
</tr>
<tr>
<td>$R_s$</td>
<td>stabilising resistance</td>
<td>K</td>
</tr>
<tr>
<td>$T_g$</td>
<td>absolute gas temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$T_{1,2}$</td>
<td>inlet and outlet gas temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$T^*$</td>
<td>gas temperature at sonic velocity location</td>
<td>°C</td>
</tr>
<tr>
<td>$U$</td>
<td>gas velocity</td>
<td>m/s</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>rotational velocity</td>
<td>r/s</td>
</tr>
<tr>
<td>$V_o$</td>
<td>supply voltage</td>
<td>V</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>ratio of specific heat capacity of gas</td>
<td>-</td>
</tr>
<tr>
<td>$n$</td>
<td>electrical to optical efficiency</td>
<td>-</td>
</tr>
<tr>
<td>$n_{elec}$</td>
<td>fractional coupling of electrical energy to the upper laser level</td>
<td>-</td>
</tr>
<tr>
<td>$n_{ext}$</td>
<td>fractional output power extraction efficiency</td>
<td>-</td>
</tr>
<tr>
<td>$n_q$</td>
<td>quantum efficiency</td>
<td>-</td>
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<tr>
<td>$n_{tot}$</td>
<td>total conversion efficiency</td>
<td>-</td>
</tr>
<tr>
<td>$n_v$</td>
<td>fractional mode volume</td>
<td>-</td>
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<tr>
<td>$\mu_o$</td>
<td>permeability of free space ($4\pi \times 10^{-7}$)</td>
<td>H/m</td>
</tr>
<tr>
<td>$\rho$</td>
<td>gas density</td>
<td>kg/m$^3$</td>
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<td>$\lambda$</td>
<td>wavelength</td>
<td>m</td>
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CHAPTER ONE

1.0 INTRODUCTION

The high power CO₂ laser (above 500 W) has for many years now been identified as an important addition to the vast range of machine tools available to industry for materials processing applications. The CO₂ laser is used throughout many industries in areas including cutting, welding, heat treatment and surface cladding of materials providing significant advantages over more conventional processes. The use of lasers is well suited to automated processes requiring high precision, computer controlled processing of both metals and non-metals offering previously unattainable levels of quality. The high power output and high conversion efficiency of the CO₂ laser has contributed to the many research and development programmes that have enabled the laser to move rapidly from the laboratory equipment stage into the factory floor machine tool. The more widespread integration of high power CO₂ lasers into industrial environments has however been limited by the high capital cost and by some of the more common problems associated with these lasers. These problems include the large size, poor reliability, complex servicing procedures requiring skilled personnel and also the more fundamental problems associated with the stability and performance of the electric discharge used to excite the laser.

Many of the lasers commercially available today use discharge technology developed in the 1970's which has to some extent limited the development of modern industrial laser systems. Several national programmes have been undertaken to develop new CO₂ laser technology that meets the needs of the industrial user, programmes such as the Japanese Ministry of International Trade and Industry (MITI) research programme and the recently initiated European EUREKA programme. The eight year MITI programme was aimed at developing new laser technology
to meet the future materials processing requirements of Japanese industry and to establish an export market to other industrialised nations. CO₂ lasers with laser output powers in the range of 0.5-20 kW were developed with around 53% of the lasers sold in Japan in the 100 W - 1 kW range and 41% in the 1-5 kW range. The trend worldwide appears to be toward more lasers being used in the 1-5 kW range. Much of the work has concentrated on the use of radio frequency (rf) or rf-assisted glow discharges which has probably contributed to the tendency of laser manufacturers in Europe and USA to apply rf discharge techniques to their new high power CO₂ lasers. Japan has in the last eight years developed CO₂ laser technology which is competitive with lasers produced in the West and which seems to have influenced greatly the philosophy of excitation methods in high power CO₂ lasers worldwide.

Recently much work has been carried out with rf excitation of high power CO₂ lasers in an attempt to overcome the discharge problems characteristic of many conventional dc excited lasers and to increase the laser output power from ever decreasing sizes of equipment. Although the rf techniques can offer certain advantages over dc discharges in terms of the stability and uniformity of the discharge at higher gas pressures, less constriction to the gas flow through the cavity and potentially reduced gas contamination, the cost and complexity of using rf are both substantially greater than dc at the high discharge powers required for multikilowatt laser output powers. Much of the research carried out on electric discharge CO₂ lasers has been orientated to rf techniques to the exclusion of research into the behaviour and characteristics of high power dc glow discharges. The dc glow discharge can be operated at higher specific powers than the rf discharge and can support even higher laser output powers by
suitable design of the discharge system. The majority of high power CO₂ lasers installed in industry are dc excited making the potential for significant improvements in discharge performance very great. The work contained in this thesis is concerned with the possibility of making such improvements.

1.1 Structure of the thesis

The structure of the thesis is summarised in Fig 1.1. The principles of CO₂ lasers are described in Chapter 2 which include the spectroscopy of the CO₂ molecule and the fundamental processes and mechanisms relating to the operation of a CO₂ laser. The gas requirements and the methods available to extract laser power from the cavity are also described.

A review of high power CO₂ lasers is presented in Chapter 3 which includes a description of the types of CO₂ laser, their characteristic limitations and some of the methods used to increase the performance of CO₂ lasers. A review of glow discharges relevant to the excitation of CO₂ lasers is given in Chapter 4 which includes the theory and physical characteristics of each region of the glow discharge. Multiple glow discharges are introduced and the stabilising requirements of glow discharge considered.

Chapter 5 describes the initial experimental work carried out on multiple glow discharges in a flowing gas. Different electrode configurations are investigated and the conditions required to increase the current at which the glow to arc transition occurs established. Chapter 6 describes the investigations carried out to study methods of uniformly distributing high power glow discharges and
includes work using aerodynamic techniques, magnetic rotation of glow discharges and high pressure gas injection into the glow discharge. A high flow rate gas recirculating laser was built to achieve near sonic velocity gas flows. Chapter 7 describes the application of multiple glow discharges with gas injection anodes to an ultra compact 5 kW CO\textsubscript{2} laser. The electrical, optical and gas flow characteristics of the laser were studied and optimised.

The conclusion of the work and the recommendations for further research are presented in Chapter 8. The derivation and solution of the compressible fluid flow equations for the laser cavity is given in Appendix 1. The computer programs developed for the data acquisition system described in Chapter 6 are given in Appendix 2.
(1) Introduction

(2) Principles of CO_2 lasers

(3) Review of published work on high power CO_2 lasers

(4) Review of glow discharges

(5) Preliminary experimental work

(6) Fast axial flow closed loop laser

(7) High power gas injection laser system

(8) Conclusions and recommendations for further work

References

Appendices - 1. Derivation and solution of compressible fluid flow equations for the laser
2. The computer programs developed for the data acquisition system

Fig 1.1 Structure of the thesis
CHAPTER TWO

2.1 SPECTROSCOPY OF THE CO₂ MOLECULE

2.1.1 Vibrational Energy Levels

The carbon dioxide molecule is linear and symmetric in configuration and has three degrees of vibrational freedom Fig 2.1. For the asymmetric stretch mode (Fig 2.1 (b)) the atoms of the molecule vibrate along the internuclear axis in a symmetrical manner and in the bending mode (Fig 2.1 (c)) the vibration of the atoms is perpendicular to the nuclear axis. In the asymmetric stretch mode (Fig 2.1 (d)) the atoms vibrate along the internuclear axis in an asymmetrical manner. The vibrational state of the molecule is described by three quantum numbers, \( n_1 \), \( n_2 \) and \( n_3 \) and is usually written in the form \( (n_1 n_2 n_3) \) where \( n_1 \) describes the number of vibrational quanta in the symmetric stretch mode, \( n_2 \) the number of vibrational quanta in the bending mode and \( n_3 \) the number of vibrational quanta in the asymmetric stretch mode. Each of these vibrations can be identified by a characteristic frequency \( f \). The observed fundamental frequencies for the CO₂ vibrations are \( f_1/2 \pi c = 1337\text{cm}^{-1} \), \( f_2/2 \pi c = 667\text{cm}^{-1} \) and \( f_3/2 \pi c = 2349\text{cm}^{-1} \) (Martin & Baker 1962). The energy diagram for the lower vibrational levels of the CO₂ and N₂ molecules is illustrated in Fig 2.2.

The level designated \((001)\) is the upper laser level and the \((100)\) and \((020)\) the lower laser levels. Molecules which are excited from the ground state to the lower laser levels decay back to the ground state through radiative and collision induced transitions to the lower \((010)\) level, which in turn decays to the ground state \((000)\). The \((001)-(100)\) vibrational-rotational transitions produce an emission of
Fig 2.1 Vibrational modes of the CO$_2$ molecule
infrared radiation near 10.6 microns and the (001)-(020) transitions produce an emission near 9.6 microns. Other emissions can occur but these are relatively weak compared to the above emissions. One emission corresponds to the (010)-(000) transition and emits radiation at 15.4 microns and the other emission corresponds to the (001)-(000) and emits radiation at 4.3 microns (Cheo 1971). The transition from (100)-(010) is forbidden by the Selection Rules and any other emissions are very weak.

2.1.2 Rotational Structure of the CO₂ Molecule

Each vibrational energy level of the CO₂ molecule's electronic ground state contains a number of rotational energy levels due to the rotation of the molecule Fig 2.2.

The rotational level is characterised by a quantum number J, and has a degeneracy of (2J+1) and the energy is given by

\[ E_J = \hbar c BJ(J+1) \]  

(1)

where \( \hbar \) is Planck's constant, \( c \) the velocity of light and \( B \) is a rotational constant given by

\[ B = \frac{\hbar}{8\pi^2 I c} \]  

(2)

where \( I \) is the moment of inertia of the rotating molecule. The average value of \( B \) for all the rotational levels considered is 0.387 cm⁻¹ (Demaria 1973) at a temperature of 400 K. From equation (1) \( E_J \) increases with the quantum number \( J \). The population \( N_J \) of any given
Fig 2.2 Energy level diagram of lower vibrational levels of $\text{CO}_2$ and $\text{N}_2$
rotational level with respect to the total population $N_i$ can be described by a Boltzmann distribution

$$N_J = N_i \frac{(2J+1) \hbar c B \exp \left[ -\frac{\hbar c B(J+1)}{K T_g} \right]}{K T_g}$$

where $K$ is the Boltzmann constant and $T_g$ the absolute gas temperature. The rotational level with the maximum population can be found from (3) by differentiation of $N_J$ with respect to $J$ and equating to zero to find the maxima.

$$J_{\text{max}} = \left[ K T_g \right] - \frac{1}{2}$$

For a typical range of operating gas temperatures in a CO$_2$ laser of 300 K to 400 K, $J_{\text{max}}$ ranges from 17 to 20.

2.1.3 Population Inversion and Depopulation

Stimulated emission of radiation can be obtained in a gas through the use of a glow discharge. The energetic electrons produced in the discharge collide with the gas molecules exciting them to higher energy levels from which they spontaneously descend to lower energy levels emitting the excess energy in the form of photons or quanta of light. To obtain the optical gain that characterises laser action it is necessary that the population density of particles in the upper laser levels exceeds that of the lower energy levels. This condition is known as population inversion.

To achieve high output powers for a given transition between a
pair of energy levels it is also necessary that the total number of molecules excited to the upper laser level be large and that the gas molecules leave the lower laser level as fast as they arrive from the upper laser level. This depopulation or de-excitation of the lower laser levels is as important as the excitation to the upper laser levels since a molecule that has already contributed to laser output must return to the ground state before it is available again for excitation to the upper laser level.

The techniques used to excite and depopulate the molecules in the gas are discussed in sections 2.4 and 2.5.

2.2 Quantum Efficiency and Working Efficiency

The energy expended by molecules in returning from the lower laser level back to the ground state contributes nothing to the power output of the laser. A proportion of energy is therefore wasted for every molecule that makes the laser transition. This amount of energy wasted by a molecule is equal to the difference between the energy needed to excite the molecule to the upper laser level and the energy of the photon of light that is emitted when the molecule makes the transition from the upper to lower laser level. The ratio of these two quantities - the emitted energy divided by the excitation energy - is a measure of the maximum theoretical efficiency with which the laser can operate. This efficiency is termed the quantum efficiency of the laser. This assumes that every molecule that is excited to the upper laser level contributes one photon of laser radiation and also that no other transitions such as to lower energy levels occur.

The emitted energy of the photon is given by
\[ E_1 = E_{001} - E_{100} \text{ for 10.6 microns } E_1 = 960 \text{ cm}^{-1} \]
\[ E_2 = E_{001} - E_{020} \text{ for 9.6 microns } E_2 = 1060 \text{ cm}^{-1} \]

The ratios of \( E_1 \) and \( E_2 \) to \( E_{001} \) represent the quantum efficiencies (QE) at the two dominant output wavelengths

\[ \text{QE}_1 = 41\% \text{ at 10.6 microns} \]
\[ \text{QE}_2 = 45\% \text{ at 9.6 microns} \]

These quantum efficiencies are two of the highest for any type of laser in operation and make the CO\(_2\) laser one of the most attractive for obtaining high power outputs. Only the CO and the pulsed, electron beam initiated HF chemical laser have been reported with higher efficiencies (Svelto 1982).

The efficiency of a laser is considerably lower than the quantum efficiency as no ideal means exists for selectively exciting the gas particles from the ground state to the upper laser level. For example to excite a molecule from the ground state to the upper laser level requires a collision with an electron of a precise energy. A gas discharge contains electrons with a range of kinetic energies. Collisions with these various electrons will excite molecules not only to the upper laser level but also to other energy levels from which they would contribute nothing to the laser output. Only a fraction of the electrical input to the gas discharge is therefore effective in exciting molecules to the upper laser levels. The operation of the discharge can be optimised to increase the probability of electrons existing in the discharge of the most desirable energy level. This increases the probability of collisions resulting in excitation to the
upper laser levels only (Section 2.4). The ratio of the laser output power to the electrical input power to the discharge is termed the working efficiency of the laser.

The excitation of molecules which results in laser output is dependent upon processes which take place in the positive column of the discharge; the electrode fall regions do not contribute to these processes. The electrode fall regions associated with the short discharges found in transverse flow lasers represent a larger fraction of the discharge voltage than in the longer axial flow discharges. The total discharge voltage with a transverse flow laser is about 1000 V with fall voltages of 200-300 V which represents a significant percentage of the total voltage. Transverse lasers will for this reason usually have a lower working efficiency than fast axial flow lasers.

2.3 EXCITATION MECHANISMS

2.3.1 Direct Electron Impact

The efficient transfer of energy from energetic electrons in the discharge to the upper vibrational levels of N$_2$ and CO$_2$ can occur in mixtures of He:N$_2$:CO$_2$ by direct elastic and inelastic collisions with molecules of N$_2$ and CO$_2$. The transfer of energy through elastic collisions is negligibly small compared with inelastic collision processes (Engelhardt et al 1964, Hake and Phelps 1967). The efficiency of this process is dependent on the value of E/N (electric field strength/neutral particle density) of the electric discharge which is a measure of the electron temperature. For a given gas mixture there exists a value of E/N which maximises the transfer of energy. If the value of E/N is too low the electron temperature will
not be sufficient to excite the lower laser levels and if it is too high it may lead to excitation of higher transitional levels and to excessive ionisation of the gas which can result in discharge instability.

At present there exists no experimental technique with the resolution required to determine the exact electron energy distribution within an electric discharge condition. Analytical techniques (Nighan 1969, 1970) have to be applied using the available collision cross-section data (Schulz 1962, Engelhardt et al 1964).

Fig 2.3 presents the fractional power transferred from the electrons to N₂ and CO₂ molecules as a function of E/N and average electron energy. Although the calculations for this graph were made for a gas mixture of CO₂:N₂:He (0.1:0.1:0.8 by mass) small variations in the mixture will not significantly influence the fractional power transfer (Nighan 1969). For an E/N value of approximately $10^{-16}$ V.cm⁻², 65% of the electron energy goes directly into the CO₂ (001) upper level and effectively all the energy goes into vibrational excitation of either CO₂ or N₂. For an E/N of about $10^{-15}$ V.cm⁻², more than 80% of the electron energy goes into electronic excitation of CO₂ and N₂. Therefore an E/N range of $10^{-16}$ V.cm⁻² can be considered to be a transition region between electronic and vibrational excitation by electron energy transfer. Electronic excitation although not a predominant electron energy loss process, is a necessary part of sustaining ionization in the electric discharge.

For an average electron energy of 1 eV (typical of electrons present in glow discharges in He:N₂:CO₂ mixtures), the fractional power transfer coupled to the CO₂(001) and N₂(V=n) system is around
Fig 2.3 Fractional electron power transfer to $\text{CO}_2$ and $\text{N}_2$ in a
(10% $\text{CO}_2$, 10% $\text{N}_2$, 80% He) gas mixture (Nighan
and Bennet 1969)
Combining this with the 41% quantum efficiency of the 10.6 micron transition indicates that the maximum electrical to optical efficiency is approximately 30% (DeMaria 1973). Higher efficiencies should be obtainable if independent control of the E/N and ionization of the discharge is maintained. Preionization techniques such as electron beam (EB), ultra violet radiation, gas additives and high frequency discharges should all increase the efficiency of the laser.

2.3.2 Resonant Energy Transfer and the Role of the Nitrogen Molecule

The addition of nitrogen gas to the active medium results in the selective excitation of the CO\textsubscript{2} molecules to the upper laser level (001). Since nitrogen is a diatomic molecule it has only one degree of vibrational freedom, hence one vibrational quantum number (n) completely describes its vibrational energy levels. Nitrogen molecules can be efficiently excited from the n=0 to n=1 level by inelastic electron collisions in a low pressure gas discharge. The energy of excitation of the N\textsubscript{2}(n=1) molecule is only 18 cm\textsuperscript{-1} below the CO\textsubscript{2} (001) level and so efficient transfer of vibrational energy can take place from the N\textsubscript{2}(n=1) molecules in collision with CO\textsubscript{2}(000) molecules. The collision results in the CO\textsubscript{2} (000) molecule being excited to CO\textsubscript{2} (001) upper laser level and the N\textsubscript{2}(n=1) returns to the ground state having lost one quantum of vibrational energy. This increase in efficiency of the laser was discovered almost simultaneously by Legay and Lagay-Sommaire (1964) and by Patel (1964c,d,e) shortly after Patel's (1964a,b) first report of laser action in a CO\textsubscript{2} gas. Patel observed an increase in average power of the laser from around 1 mW to 11.9 W with a 3% electrical to optical conversion efficiency.
2.4 RELAXATION PROCESSES

Efficient excitation processes used to populate the upper laser level $\text{CO}_2$ (001) enable high power laser outputs to be realised only if efficient relaxation processes exist to depopulate the lower laser level (100) and the intermediate level (010). The molecules at the lower laser level (100) are de-excited essentially through collisions with other molecules. The lower laser level (100) has nearly twice the energy required to excite a ground state (000) molecule to the (010) level. Thus a resonant vibrational energy transfer mechanism ensures efficient de-excitation of the (100) molecules (Fig 2.4 (a)).

\[
\text{CO}_2(100) + \text{CO}_2(000) \rightarrow \text{CO}_2(010) + \text{CO}_2(010)
\]

(a)

\[
\text{CO}_2(010) + \text{foreign gas particle} \rightarrow \text{CO}_2(000) + \text{foreign energy gas particle} + \text{K.E.}
\]

(b)

Fig 2.4 A relaxation mechanism for depopulating the lower vibrational energy levels.

The de-excitation of the (010) molecules to the ground state is a non-resonant mechanism governed only by molecular collisions to produce kinetic energy. This process is relatively slow compared to the rate of excitation to the upper laser level and the de-excitation to the lower laser levels and can therefore result in a restriction in the
overall cycle of excitation and de-excitation. The population of the (010) level can be reduced by cooling of the medium. The addition of He gas to the CO$_2$ and N$_2$ laser mixture both aids in the cooling of the medium because of its high thermal conductivity and specific heat capacity and also collides with the (010) molecules without affecting the selective excitation of the upper laser level (Moeller and Rigden 1965).

2.5 GAS FLOW REQUIREMENTS OF THE THERMALLY LOADED LASER CAVITY

The electrical energy associated with the glow discharge is dissipated in the form of acceleration and heating of the flowing gas and the laser output beam. The laser radiation can be considered to be a constant fractional part of the electrical input to the gas and may be represented by the following equations

$$P_e = P_g + P_o$$  \hspace{1cm} (5)

and

$$P_g = (1-\eta) P_e$$  \hspace{1cm} (6)

where

- $P_e$ = electrical power input
- $P_g$ = thermal power dissipated in the flowing gas
- $P_o$ = laser output power
- $\eta$ = electrical to optical efficiency

The average temperature rise of the gas can be calculated from

$$P_g = \dot{m} C_p (T_2 - T_1)$$  \hspace{1cm} (7)

where

- $\dot{m}$ = mass flow rate of flowing gas
- $C_p$ = specific heat capacity at constant pressure
\[ T_2 = \text{gas exit temperature from laser cavity} \]
\[ T_1 = \text{gas inlet temperature} \]

Equation (7) is represented in Fig 2.5 for a range of temperature rises. This simple treatment of the thermally loaded laser cavity enables estimates to be made of the amount of gas required to maintain a certain discharge power and hence laser output power for any particular value of gas temperature and electrical to optical efficiency. For a laser output power of 1 kW at an electrical to optical efficiency of 10% and a gas temperature rise of 200°C, a gas flow of around 0.016 kg/s would be required.

A more sophisticated technique applying the compressible gas laws (Shapiro 1953) to a flowing gas with heat addition enables the maximum specific power loading of the flowing gas to be calculated for a given set of inlet flow conditions and cavity geometry. This would enable estimates to be made of the inlet to outlet flow conditions including the pressure, temperature, density and velocity ratios of the flowing gas and also the maximum thermal loading of the gas to maintain unchoked, subsonic flow conditions in the laser cavity. The maximum thermal loading of the gas gives a quantitative measure of the utilisation of the gas and hence whether higher electrical power inputs to the gas could be sustained. The equations governing this type of compressible fluid flow have been solved here (Appendix 1) for the fast axial flow laser and a computer program written to enable the inlet to outlet flow ratios and the maximum specific power loading of the gas to be determined for a given laser cavity geometry and inlet flow conditions.

A set of results for the laser described in Chapter 7 are shown in
Fig 2.5 Variation of electrical discharge power with gas flow rate for different gas exit temperatures.
the graph in Fig 2.6 which illustrates the dependence of the specific power loading of the gas on the gas entrance velocity (Mach number) and gas exit temperature. The maximum gas exit temperature is about 270°C (limited by the thermal depopulation of the lower lasing levels) and under the specific conditions which correspond to the 5 kW laser described in Chapter 7, the maximum electrical power loading of the gas for an inlet Mach number of 0.33, is about 680 kW/kg/s. The application of this program enables the effects of changing the geometry of the laser cavity, gas mixture, flow rate, pressure and conversion efficiency of the laser on the gas flow characteristics to be determined.

2.6 THE EFFECTS OF GAS CONTAMINATION ON THE ELECTRIC DISCHARGE

A major factor which has limited the operation of closed-cycle, CW high power CO₂ lasers has been the effect of contamination of the lasing gas. This contamination can occur through plasma-induced chemical reactions, hydrocarbon oil vapour from pumps used to recirculate the gas and from ingestion of air through vacuum leaks in the laser.

The plasma-induced chemical reactions are associated with the dissociation of carbon dioxide to carbon monoxide and also the oxidation of nitrogen. All of these reactions result in a decrease in gain of the lasing medium, a change in the discharge impedance and have a destabilising effect on the glow discharge. The chemical reactions are summarised in Fig 2.7 and the effect of the nitrogen-oxygen reactions summarised in Table 2.1. The nitrogen-oxygen compounds were found to cause the greatest decrease in gain of the lasing medium and to cause the most plasma instabilities.
Fig 2.6 Variation of gas exit temperature with entrance Mach number for different specific power loadings.

Gas exit temperature (°C)

900 kW/kg/s
800
700
600
500
300
100

Inlet Mach number
Laser gas mixture

Mixture partially dissociates in electric discharge

Dissociation products recombine

Fig 2.7 Summary of plasma induced chemical reactions in a CO$_2$ laser mix
The degree of contamination of the lasing medium in a recirculating gas laser is dependent upon many factors including the discharge electric field strength, the discharge current density, the gas mixture, the dwell time of the gas in the discharge and the materials used for the electrodes and construction of the gas recirculating path. The effects of the contamination on the laser performance can be reduced by either using two catalytic reactors to selectively remove the oxides of nitrogen and recombine the carbon dioxide or by allowing a constant purge of fresh gas into the laser so that over a period of time all the laser gas is replaced. Typical flow rates of purge gas correspond to 0.1-1% of the total flow rate recirculated around the laser (Hoag et al 1974, Lancashire et al 1977).

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Effect</th>
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<tr>
<td>NO</td>
<td>Gain and plasma impedance begin to decrease at 0.1% (1000 ppm); complete loss of gain at 1.5% (15000 ppm).</td>
</tr>
<tr>
<td>NO₂</td>
<td>0.04% (400 ppm) caused plasma instabilities; complete loss of gain at 0.1% (1000 ppm).</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.08% (800 ppm) caused plasma instabilities; complete loss of gain at 0.2% (2000 ppm).</td>
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Table 2.1 Summary of Nitrogen-Oxygen Contamination Effects (After Tannen et al 1974).
Contamination from oil vapour in the gas recirculating pump(s) is most severe with Roots blowers which have two oil-filled gearboxes from which oil can enter the laser system via shaft seals. The oil not only decreases the stability of the discharge but is also deposited on the resonator optics reducing their efficiency and operating life. The level of contamination can be kept below 100 ppm (identified as the maximum allowable level - Ashcroft 1984) by the use of either special sealing techniques or by differentially pumping the gear boxes to maintain a lower gas pressure in these regions thus preventing the passage of oil into the laser.

Atmospheric contamination through vacuum leaks in the laser lead to increased levels of oxygen which combine with nitrogen in the discharge resulting in degradation of laser performance. Vacuum sealing techniques can be applied to keep the overall leak rate of the laser below $10^{-5}$ mb.l/s which has been found to be a practical level to maintain good long term stability of the lasing gases (Budgen 1986).

2.7 OPTICAL CAVITY THEORY

2.7.1 Resonant Modes and Mode Selection

To achieve high rates of stimulated emission of photons in the optical medium, it is necessary to provide a strong electromagnetic field. If the frequency of this field is close to the frequency of the spontaneously emitted wave, there is a finite probability that the electromagnetic wave will stimulate further emissions from the medium. The transverse and longitudinal distribution of electromagnetic waves in the laser cavity are critically dependent upon parameters including
the mirror separation, the discharge tube diameter, the output coupler reflectivity and the radius of curvature of the mirrors. The standing wave system in the resonant cavity consists of two waves travelling in opposite directions - the partially transmitting output window allowing a fraction of this field to leave the cavity as the output beam. The emitted radiation from this window being the laser beam. The spatial distribution of the laser beam will resemble the transverse distribution of energy within the resonant cavity. Shapes of selected transverse electromagnetic (TEM) modes are shown in Fig 2.8, the number of dark stripes in the patterns corresponds to the subscripts. There are many transverse modes in which the laser may oscillate, but the precise mode of oscillation will depend upon the losses (both diffraction and scattering) associated with each mode. The dominant mode will be the one associated with the least losses. Oscillation of the laser in the fundamental TEM\(_{00}\) mode will occur only if the diameter of the mode has nearly the same diameter as the discharge tube or other dimension limiting aperture (Bloom 1963). The mode diameter cannot be larger than this or large diffraction losses will occur which would prevent the laser from oscillating at all. If it is much smaller than this, then higher order modes will have sufficiently small diffraction losses to be able to dominate the lower order modes and a multimode output beam will result.

The losses associated with individual modes depend on factors such as the optical quality and the surface cleanliness of the mirrors. For example, a particle of lint located at the centre of the lowest order mode might provide a condition for a negligible increase in the diffraction losses for the TEM\(_{01}\) mode (because it would lie at a node in the electric field), but would provide a relatively high scattering loss for the lowest order modes. Under
Fig 2.8 Typical modes of a gas laser oscillator (Kogelnik and Li 1966)
these conditions, the total losses (diffraction plus scattering) of the TEM\textsubscript{01} mode might fall below that of the TEM\textsubscript{00} mode and the laser would preferentially oscillate in the higher order mode. Since in practice dust particles and other imperfections may always be present the actual ratio of losses for the two modes compared to the theoretical losses, will vary over wide ranges for different lasers and even for the same laser at different times.

The higher order modes occupy larger volumes within the cavity than the TEM\textsubscript{00} mode and are therefore able to interact with more of the lasing medium and extract more power from the laser cavity.

2.7.2 Stability of Cavity

A stable resonator is defined as one in which rays can be trapped by the curvature of two mirrors aligned parallel to each other and will oscillate indefinitely. It is usually not possible to tell just from casual inspection whether a resonator is stable or not - it depends upon the exact radii of curvatures and the mirror separation. Unstable resonators will lase if the lasing medium has sufficiently high gain per unit length to compensate for the limited number of round-trips a ray will make before leaving the resonator. Resonator stability is therefore of more concern at lower gain levels.

A simple test has been devised for determining resonator stability (Fox and Li 1962). The curvature of the two mirrors are defined as $R_1$ and $R_2$ and the mirror separation $l$. If the mirror is convex the radius is negative. The condition for stability is

$$0 < (1-1/R_1)(1-1/R_2) < 1$$ (8)
Equation (8) is illustrated in Fig 2.9. Several resonator configurations are illustrated on the diagram; the shaded areas denote unstable resonators. If a resonator configuration lies well inside the stable region then the low order modes will in general be confined along the axis of the cavity and the associated diffraction losses will be small. The loss due to diffraction increases rapidly across the boundary from the stable region to the unstable region.

The Fresnel number is a parameter that can be used to indicate the power loss per transit of a photon through travelling through the resonator. The Fresnel number may be defined by

\[ N = \frac{r_1 r_2}{\lambda l} \]

where \( N \) is the Fresnel number, \( r_1 \) and \( r_2 \) are the radii of the beam at the resonator mirrors, \( l \) is the mirror separation and \( \lambda \) the wavelength of the ray. High Fresnel numbers characterise cavities with low diffraction losses that will support the fundamental TEM\(_{00}\) mode.

2.7.3 Types of Cavity

Optical resonators of various geometries for use in lasers have been studied by Kogelnik and Li 1966, Boyd and Kogelnik 1962, Fox and Li 1963 and Bloom 1963.

Several different resonator geometries are illustrated in Fig 2.10. The type of resonator selected for a laser will depend upon the following criteria:
Fig 2.9 Resonator stability diagram with a number of resonator configurations (after Kogelnik and Li 1966)
Fig 2.10 Laser resonator configurations
(1) the sensitivity of the resonator to angular misalignment of the mirrors
(2) the angular divergence of the output beam
(3) the efficiency at which power may be extracted from the active medium
(4) the beam diameter and mode structure

The dependence of the above properties of the laser on the three variables of mirror separation, tube diameter and mirror radius of curvature is summarised in Tables 2.2 and 2.3 which illustrate the changes that will occur for increases in mirror separation, mirror radius of curvature and tube diameter.

The plane parallel resonator in Fig 2.10(a) is very sensitive to angular misalignment of the mirrors and has large diffraction losses. The large diffraction losses produce a phase lag near the edges of the beam which gives the wave front a slight curvature and as a result the output wave is actually diverging by an amount slightly greater than the expected divergence due to diffraction effects alone. The sensitivity of the mirror alignment of this configuration usually precludes its use in continuous wave (CW) lasers. This configuration is only just stable making it extremely sensitive to the optical flatness of the mirrors (typically 1/100 wavelength). The large radius of curvature mirror, Fig 2.10(b) configuration, combines the high utilisation of the cavity characteristic of the plane parallel arrangement but with a reduced sensitivity to the mirror alignment. This configuration results in an output beam of approximately the diameter of the discharge tube thus utilising a high percentage of the excited species in the laser and potentially developing high output
### Table 2.2 Effects of changes in mirror separation, radius of curvature and diameter on laser characteristics

<table>
<thead>
<tr>
<th>CHANGES IN</th>
<th>Sensitivity to angular misalignment</th>
<th>Probability of low beam divergence</th>
<th>Probability of high utilisation of laser cavity</th>
<th>Probability of low order modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase in mirror separation</td>
<td>↑</td>
<td>↑</td>
<td>↓</td>
<td>↑</td>
</tr>
<tr>
<td>Increase in radius of curvature of mirror</td>
<td>↑</td>
<td>↓</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>Increase in tube diameter</td>
<td>↓</td>
<td>↓</td>
<td>↑</td>
<td>↓</td>
</tr>
</tbody>
</table>

### Table 2.3 Summary of resonator characteristics

<table>
<thead>
<tr>
<th>Resonator Type</th>
<th>Sensitivity to mirror alignment</th>
<th>Stability of resonator</th>
<th>Utilisation of laser cavity</th>
<th>Low order mode quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane parallel</td>
<td>critical</td>
<td>very low</td>
<td>excellent</td>
<td>poor</td>
</tr>
<tr>
<td>Large radius of curvature</td>
<td>high</td>
<td>low</td>
<td>good</td>
<td>poor</td>
</tr>
<tr>
<td>Confocal</td>
<td>low</td>
<td>high</td>
<td>medium</td>
<td>good</td>
</tr>
<tr>
<td>Spherical</td>
<td>critical</td>
<td>very low</td>
<td>poor</td>
<td>good</td>
</tr>
<tr>
<td>Hemispherical</td>
<td>high</td>
<td>low</td>
<td>poor</td>
<td>good</td>
</tr>
<tr>
<td>Plano-concave</td>
<td>high</td>
<td>low</td>
<td>good</td>
<td>poor</td>
</tr>
</tbody>
</table>

Table 2.2 Effects of changes in mirror separation, radius of curvature and diameter on laser characteristics

Table 2.3 Summary of resonator characteristics
powers. The alignment of the mirrors is still very critical compared with the hemispherical resonator but is practical. The confocal resonator uses mirrors with radii of curvatures equal to the mirror separation Fig 2.10(c). The diagram illustrates the reduction in utilisation of the laser cavity but there is an increase in the level of stability and ease of optical alignment. The main disadvantage of this configuration is if the mirror radii are not exactly equal. The configuration is stable if $R_1 > 1$ or if $R_2 < 1$ but is not stable if $1$ lies between these two values. It is thus necessary when working with confocal resonators to have adjustment of the mirror separation to ensure stable operation of the cavity. The spherical resonator Fig 2.10(d) consists of two mirrors separated by twice their radii ie such that the surfaces of the mirrors are defined by a sphere of diameter 1. The mode volume is large at each end of the cavity but focuses down to a diffraction limited spot at the centre. The general properties are the same as for the hemispherical resonator except that the alignment of the mirrors is extremely critical because the mirrors must be coaxial with one another and have the individual radii of curvature coincident with the diffraction limited spot. The hemispherical resonator consists of one spherical mirror and one flat mirror placed at approximately the centre of curvature of the sphere Fig 2.10(e). The utilisation of the cavity is good at one end and very poor at the other, resulting in only 30% of the cavity being utilised. The major advantage of this configuration is the ability to choose the mode dimension by small variations in mirror separation. As the mirrors are moved closer together the mode diameter decreases and the output power and stability are increased. The resonator is also extremely tolerant to misalignment of the mirrors making it a useful configuration for experimental work. The plano-concave resonator Fig 2.10(f) behaves very similarly to the large radius of
curvature resonator but with improved utilisation of the laser cavity and a smaller tolerance to angular misalignment of the mirrors.

2.7.4 Unstable Resonators

A resonator can be described as unstable when an arbitrary ray, travelling back and forth between two aligned mirrors, will diverge indefinitely away from the resonator axis. The cross-sectional area of low order modes in stable resonators tends to be small which limits the utilisation of the lasing medium, particularly in high power CO₂ lasers where it becomes attractive to try and increase the power of the laser by increasing the cross-sectional area of the electric discharge. As the cross-sectional area of the optical resonator is increased the Fresnel number decreases and it becomes progressively more difficult to operate the laser with a stable low order mode output using a stable resonator. Unstable resonators can provide a large mode volume in a single transverse mode enabling high utilisation of large cross-sectional area laser cavities. The rays diverge out of the resonator after only a few oscillations and therefore these resonators have substantially greater (geometrical) losses than those of a stable resonator (where the losses are due mainly to diffraction). These geometrical losses can however be turned into useful output coupling through the use of an intracavity mirror. A typical positive branch confocal unstable resonator is shown in Fig 2.11 with an intracavity mirror.

The advantages of using an unstable resonator can be summarised as follows: (i) large, controllable mode volume, (ii) good transverse mode discrimination, (iii) all reflective optics. The main disadvantages are as follows: (i) the laser output beam is in the form
Fig 2.11 A positive branch confocal unstable resonator with intracavity mirror
of an annular ring with zero intensity at the centre, (ii) the intensity distribution in the beam does not follow a smooth curve, but exhibits diffraction rings and (iii) the unstable resonator is generally more sensitive to cavity perturbations compared with an equivalent stable resonator. This class of resonator is being used more widely in multikilowatt CO₂ lasers where high quality single mode diffraction limited output beams are required for materials processing applications.
CHAPTER THREE

3.0 A REVIEW OF THE DEVELOPMENT OF HIGH POWER CW CARBON DIOXIDE LASERS.

The first report of continuous wave (CW) laser action in a CO\textsubscript{2} gas or electric discharge was made by Patel (1964 a,b,). These early reports gave detailed characteristics of the CW and pulsed power performance of the CO\textsubscript{2} laser. The average power measured was approximately 1 mW with only a small increase under pulsed conditions. Similar studies were made independently by a group of French scientists in the area of molecular spectroscopic research (Legay-Sommaire et al 1965, Barchewitz et al 1965 a,b). The addition of nitrogen to the gas mixture (Legay and Legay-Sommaire 1965 and Patel 1964 c) raised the output power from the milliwatt level to tens of watts. The addition of helium to the laser medium increased the output power and the electrical to optical conversion efficiency (Moeller and Rigden 1965, Patel et al 1965). The scalability of the CO\textsubscript{2} laser to higher output powers and the high conversion efficiency was recognised and the laser was identified as having exceptional potential for industrial materials processing applications.

3.1 TYPES OF HIGH POWER CW CO\textsubscript{2} LASERS.

A number of advances have been made in the methods of exciting the CO\textsubscript{2} laser which have led to a rapid increase in the laser output power. Two major constraints have influenced the design of the CO\textsubscript{2} laser: the removal of heat from the electric discharge and the operation of the discharge at high electrical input powers. The three types of high power CW CO\textsubscript{2} lasers which will be considered here are
the slow flow, fast axial flow and transverse flow lasers. A schematic diagram of each of these is given in Fig 3.1 (a), (b) and (c) respectively. The three types of laser will be discussed in the context of the two constraints mentioned above and some of the methods used to try to overcome these constraints will be assessed.

The performance of the lasers discussed in the following sections is compared using several ratios to enable comparisons to be made between lasers of different output powers and configurations. The laser output power per unit length of discharge and the electrical input power density provide an indication of the compactness of the laser and also the effectiveness of the methods used to maintain a uniform glow discharge at high electrical power loadings. The electrical power input per unit mass flow rate of gas is an important quantity which provides a measure of how efficiently the gas is utilised in the laser. The laser output power density, electrical to optical conversion efficiency and tube diameter are also recorded for each laser. These figures are recorded where there is sufficient information reported in the literature and are summarised at the end of the chapter in Tables 3.1 and 3.2.

3.2 THE SLOW FLOW LASER

The slow flow laser relies upon conduction of the waste heat generated in the electric discharge to the water or oil cooled discharge tube. The temperature of the gas must remain below about 500 K to maintain a high conversion efficiency. The rate of heat transfer from the gas to the discharge tube walls (Swartz and Margalith 1974, Laderman and Byron 1971) limits the maximum laser power obtainable from this configuration to approximately 100 W/m.
Fig 3.1 Schematic diagrams of the slow flow, fast-axial flow and transverse flow CO₂ lasers
slow flow of gas (typically 60-70 l/s, Patel et al 1965) is passed through the system to remove dissociation products before a large concentration builds up and reduces the gain of the active medium (Smith 1968, Weigand et al 1970 and Tannen et al 1974). An increase in the tube diameter increases the tendency of the gas to overheat at the centre of the tube because of the longer conduction path to the cooled surfaces of the discharge tube, thus no increase in laser power per unit length of discharge is observed. An increase in the gas pressure increases the density and heat capacity of the medium which would result in an improvement in the heat transfer mechanism. As the gas pressure is increased the uniformity of the glow discharge decreases, the diameter is reduced and there is a greater likelihood of filamentary arcs occurring which do not contribute to laser output (Wasserstrom et al 1978).

The total output power of a slow flow laser can only be increased by using a number of discharge tubes placed optically in series so that the total length of discharge is increased. A laser using 8.2 m length of discharge was reported by Roberts (1967) and an output power of 820 W corresponding to 100 W/m length of discharge and a laser power density of 0.25 mW/mm$^3$ of cavity at a discharge current of 100 mA and an electrical to optical conversion efficiency of 22% was achieved. The longest cavity developed using many discharge tubes optically in series was 229 m long and produced a laser output power of 8.8 kW (Horrigan et al 1969).

The slow flow laser provides excellent power stability and mode structure when compared with the fast axial and transverse flow convection lasers. The constraint of low output power per unit length of discharge leads to the use of very long optical cavities with small
diameter tubes enabling all the output power to be confined to the fundamental TEM\textsubscript{00} mode without the problems of mode instability and the presence of unwanted higher order modes often associated with fast flow lasers. The discharges are very stable in the slow gas flow and the high total length of discharge leads to integration of any non-uniformity along the length of the cavity resulting in good power output stability.

The absence of rotating machinery to recirculate the laser gas contributes to the high stability of the cavity. A number of fast axial flow lasers suffer from machine vibration resulting in oscillation of the mirrors and a corresponding degradation of the beam quality. The transmission of the machine vibration is a result of inadequate isolation of the rotating machine. Many slow flow laser resonators are mounted on substantial mechanical supports such as granite (Photon Sources 500 W).

The Ferranti MF400 450 W laser utilises twenty-four water cooled discharge tubes each containing a 20 mA glow discharge arranged to form a folded cavity of 10 m. The laser develops 450 W output with an electrical to optical conversion efficiency of 10%. A range of slow flow lasers are available from Coherent with output powers of 185, 375, 525 and 775 W. The lasers each contain standard 1500 mm long discharge tubes operating at a current of 50 mA. The 185 W laser uses only two tubes while the 775 W uses eight tubes with a conversion efficiency of 8%. The laser output power per unit length of discharge is around 65 W/m. These lasers are typical examples of the slow flow CO\textsubscript{2} lasers available today.

Slow flow lasers continue to find major applications in the area
of cutting because of the good mode structure and power stability of the output beam available and good reliability compared with convection type lasers because of the inherent simplicity of design and the length of the laser cavity.

3.3 CONVECTIVE REMOVAL OF HEAT FROM THE ELECTRIC DISCHARGE

The transition from a diffusion controlled heat transfer mechanism to a convective heat transfer mechanism has been investigated in detail by Swartz and Margalith (1974). They report that if the ratio of the gas mass flow rate to the discharge length \((m/l)\) is less than \(2.5 \times 10^{-4}\) kg/ms then the discharge power per unit length is practically independent of the gas flow rate, since the conduction to the cooled side walls of the tube is the dominant heat transfer mechanism. Alternatively when the ratio \((m/l)\) is greater than \(8 \times 10^{-4}\) kg/ms the discharge power depends almost linearly on the mass flow rate provided a stable, and uniform glow discharge can be maintained in the gas flow. In this regime the dominant heat transfer mechanism is convection. It is this convective heat transfer which has enabled the laser output power per unit length of discharge to be scaled with the gas mass flow rate in gas transport convection lasers enabling multikilowatt laser performance from relatively compact lasers (Deutsh et al 1969, Tiffany et al 1969, Targ and Tiffany 1969, Hill 1970). To obtain any significant improvement in laser performance over the slow flow laser the hot gas has to be convectively removed from the laser cavity and be replaced by cold fresh gas in a time which is short when compared with the conduction thermal time constant associated with the discharge tube (Crafer and Oakley 1981). The time constant is given by
\[ t = \frac{pca^2}{6k} \]  
\[(3.3)\]

where 
- \( p \) = gas density
- \( c \) = specific heat capacity of gas
- \( a \) = tube radius
- \( k \) = thermal conductivity of the gas

A typical value of this thermal time constant is several milliseconds for a CO\(_2\) laser gas so that a gas dwell time in the laser cavity of 1 ms or less is required. Under these conditions the laser is termed a fast flow laser.

The high gas flow rate used to remove the heat from the discharge can also be used to stabilise the discharge at high electrical power loadings against the formation of arc streamers or column collapse of the glow discharge (see Section 4.6). Since the heavy positive ions in the discharge are collisionally coupled to the neutral gas molecules and since the electrons and ions are electrostatically coupled, aerodynamic forces in the flowing neutral gas species would be expected to modify the current distribution in the discharge. A precise control of the gas flow field, the velocity profile and turbulence level in these discharges can have a dramatic effect in distributing the glow discharge and in delaying constriction of the electric discharge which limits the laser output power (Eckbreth and Owen 1972 a, b).

Results reported by Nighan and Wiegand (1974) of a theoretical analysis of the stability of high power CO\(_2\) laser discharges showed that the growth time of arc instabilities in the glow discharge was of
the order of 1 ms over a wide range of pressures (27-270 mb). The flow velocity required to convectively remove heat from the laser cavity is of the order of 100-500 ms which for a typical axial flow or transverse laser cavity represents a gas dwell time of the order of 1-10 ms, a time comparable with the growth time of the instability. These observations led to the conclusion that an important role of the gas flow is not only to remove heat from the discharge but also to remove the plasma instabilities from the discharge region in a time less than that required for collapse of the discharge column to occur (Velkhov et al 1973, Wright 1963). A series of tests were conducted by Weigand and Nighan (1975) to empirically determine the dependence of the power density at which glow collapse occurred on the gas residence time in the discharge. A moveable electrode system enabled constant gas flow conditions to be maintained over a range of electrode separations corresponding to gas dwell times of between 0.3 and 10 ms. Constriction of the discharge column was found to occur for values of electrical power density of between 1-10 mW/mm³ for discharge conditions corresponding to gas residence times of between 10-1 ms respectively. These results were not very sensitive to gas pressure in the 27-270 mb range (Eckbreth and Davies 1972, Hill 1971).

3.4 GAS TURBULENCE

Experimental studies (Eckbreth and Davies 1972, Wasserstrom et al 1978, Davies 1975, Bekefi 1976 and Wiegand and Nighan 1975) have shown that non-uniformities in the gas flow velocity profile and turbulence structure significantly affect the threshold conditions for discharge instability. It has also been shown that when the turbulence level is high and the structure of that turbulence is essentially uniform, discharge stability is enhanced. If a non-uniformity is introduced to
the gas flow it results in a region of lower mass flow rate. If the electrical power input to the gas is uniformly distributed then the region where there is a lower mass flow rate is preferentially heated raising the local gas temperature and introducing a gradient in gas density and electrical conductivity. If this gradient in electrical conductivity is not dissipated by small scale turbulence then arc streamers form. This behaviour was demonstrated by Eckbreth and Davies (1972) by inserting an insulating porous wedge in the flow to create a non-uniform pressure loss and skewed velocity distribution. An arc formed preferentially on the downstream side of the wedge in this non-uniform flow region. The intensity and uniformity of the turbulence in the discharge region is therefore important in developing a uniform distribution of the electrical power input to the flowing gas (Weigand and Nighan 1975). The stability and uniformity of the discharge is found to be further enhanced if additional turbulence is introduced near the upstream electrode (Davies 1975, Weigand and Nighan 1974, Hill 1970, Ivanchenko 1969).

3.5 THE FAST AXIAL FLOW LASER

The fast flow axial flow laser (Fig 3.1 (b)) is similar to the slow flow laser (Fig 3.1 (a)) with the electric discharge, gas flow and optical path all on the same axis but it utilises a high velocity gas flow to remove heat from the laser cavity and to stabilise the electric discharge. The gas flow velocity associated with the high mass flow rates required to remove the heat from the cavity are of the order of 100-500 m/s. The gas flows are generally restricted to subsonic velocities (typically 600 m/s) at the exit to the cavity because of the constant cavity cross-section. At high subsonic velocities the gas dwell time is typically 1-5 ms enabling
high electrical power loadings to be sustained without arc formation (Weigand and Nighan 1975).

The methods employed to generate gas turbulence within the laser cavity have to leave a clear optical aperture through the laser which restricts the type of turbulence generator to either a radial gas feed(s) or to a coaxial nozzle arrangement. The laser reported by Deutsch et al (1969) incorporated a radial gas feed near the anode to create turbulence in the 25 mm diameter discharge tube (Fig 3.2). A maximum output power of 225 W was obtained from a 100 mm long discharge at an electrical to optical efficiency of 13.6%. The output power from a 13.5 mm diameter tube of 140 W yielded a laser power per unit length of discharge of 1400 W/m which represented a 14 fold increase over the 100 W/m obtained from typical slow flow lasers (DeMaria 1973). The gas flow rate of the laser was limited to only 0.42 m³/s by the pumping equipment available and corresponded to a maximum gas velocity of approximately 70 m/s. A short gas dwell time of approximately 1.4 ms was obtained by using a discharge tube only 100 mm long enabling a high power per unit length of discharge to be obtained.

Electrox manufacture. a 450 W fast axial flow laser based on the equipment reported by Deutsch (1969) incorporating four 200 mm long discharge tubes with four radial gas inlets. The gas exit velocity is reported to be as high as 560 m/s. The laser power was later increased to 1 kW by using a larger discharge tube and higher capacity Roots blower. The laser output power per unit length was increased from 562 to 1250 W/m. Further increases in the laser output power were limited by the maximum discharge current per tube (100 mA) before collapse of the glow column occurred. No further details were
Fig 3.2 Fast axial flow laser (after Deutsch 1969)
available in the literature.

A 20 W compact fast axial flow laser was reported by Tyte (1970) with a discharge length of 100 mm and tube diameter of 7 mm (Fig 3.3). The maximum output power was obtained at a discharge current of 40 mA and gas pressure of 120 mb. The gas flow rate enabled up to 1500 gas changes per second to be achieved and an equivalent power per unit length of 200 W/m. The small diameter discharge tube represented a compromise between stable operation at high gas pressure with high laser power per unit volume and the need to provide a resonator volume large enough to give adequate laser output power.

Mcleary and Gibbs (1973) reported CW operation of an atmospheric pressure fast axial flow laser incorporating radial gas feeds near the upstream anode (Fig 3.4). The gas was introduced through narrow (0.25-1 mm) gaps near the common anode at sonic velocities. The flow conditioning enabled uniform discharges to be sustained in discharge tubes 19 mm diameter, 200 mm long. The low gain associated with atmospheric pressure CO₂ lasers (due to pressure broadening) limited the output power from three discharge tubes placed optically in series to 530 W at an electrical to optical efficiency of 5% and a laser power per unit length of discharge of 883 W/m. The laser does indicate the importance of close coupling of the sonic velocity gas flow with the anode to develop unconstricted glow discharges at high pressures.

The Welding Institute originated the design of a 2 kW fast axial flow laser in 1971 which is now produced by Control Laser (Fig 3.5). The laser uses four discharge tubes 750 mm long and 34 mm diameter developing a gas exit velocity of 500 m/s. The maximum discharge
Fig 3.3 High pressure compact fast axial flow laser (after Tyte 1979)

Fig 3.4 A CW atmospheric fast axial flow laser (McLeary and Gibbs 1973)
Fig 3.5 The Control 2 kW fast axial flow laser
current per tube is 150 mA limited by the onset of arc instabilities and the maximum laser output per length of discharge is 667 W/m. The stabilisation of the discharge is achieved by rapidly expanding the recirculating gas through a coaxial nozzle which creates an axially symmetric turbulent flow field in the discharge region (Fig 3.6). Only one tungsten anode rod is used per discharge tube resulting in extremely poor utilisation of the laser cavity in the anode region. The pyrophyllite nozzle can be moved in and out of the anode head to change the flow conditions in the discharge tube. This type of shocking nozzle is typical of the flow conditioning techniques used in many commercial fast axial flow CO₂ lasers. A 7 kW version of the above laser was also developed by the Welding Institute based on the same nozzle design used in the 2 kW laser (Crafer and Pauley 1979). The laser incorporated a standard 2 kW laser as the oscillator followed by two amplifier stages optically in series (Fig 3.7). A single high capacity Roots blower was used to recirculate the gas through all the discharge tubes which were mounted together in a single framework. Although output powers in excess of 7 kW were achieved the mode quality was poor because of the inability of the oscillator adjustments to provide mode control, beam location and beam direction simultaneously.

Sugawara et al (1981) describe a 2.5 kW fast axial flow laser using two high frequency turbopumps operating at up to 18000 rpm (Fig 3.8). The laser incorporates four discharge tubes 650 mm long and 65 mm diameter developing a laser power of 960 W/m at up to 26% efficiency. The method of discharge stabilisation is by gas passing through orifices in the cathodes which creates an axially symmetric turbulent flow with the upstream electrode. The two turbopumps recirculate the laser gas at a gas pressure of 33 mb at a flow rate of
Fig 3.6 Flow conditioning nozzle used in the Control 2 kW laser
Fig 3.7 The Welding Institute 7 kW fast axial flow laser (after Crafer and Pauley 1979)

Fig 3.8 A 2.5 kW fast axial flow laser incorporating two high-frequency turbopumps (after Suguawara et al 1981)
1.76 m³/s and a differential pressure across the turbopumps of around 5 mb. The turbopumps were designed specifically for laser applications with a high volume flow rate and a high static pressure head. The maximum electrical power loading of the gas was 1.4 mW/mm³ or 330 kW/kg/s. A 5 kW version of this laser was developed (Sezima et al 1982) incorporating eight discharge tubes and two larger capacity turbopumps. The design of this laser is essentially the same as the 2.5 kW version discussed above (Sugawara et al 1981). A further development using this technology was a 20 kW fast axial flow laser reported by Sugawara et al (1984). The laser contained six discharge tubes connected optically in series, each of 134 mm diameter and 1000 mm long. Two high frequency turbopumps recirculated gas at a gas pressure of 37 mb and a volume flow rate of 8.4 m³/s. The output power of the laser per unit length of discharge was 3.3 kW/m which represents a significant improvement over the 2.5 and 5 kW lasers reported earlier and can be attributed to the much larger tube diameter of 134 mm. An unstable resonator configuration was employed to extract the 90 mm diameter beam through a zinc selenide or potassium chloride output window. The use of transmissive optics at high laser output powers (>10 kW) instead of aerodynamic windows usually employed in USA and Europe is due to the high price of helium in Japan which makes the use of wasteful aerodynamic windows uneconomical. At powers above 10 kW thermal lensing of the zinc selenide output windows can be a problem (Sparks 1971, Sherman and Frazier 1978) which is greatly reduced with KCl windows. The optics company Horriba supply KCl optics pre-coated and mounted up to diameters of 120 mm for laser power outputs up to 20 kW (Sakuragi 1984).

After the early work carried out in the area of fast axial flow
lasers (up to the mid-1970's) research efforts in the Western world became more interested in the development of high power transverse flow CO₂ lasers (Section 3.6). These devices were identified as having greater potential for developing high multikilowatt output power from compact units. As CO₂ lasers have penetrated more industrial applications the requirement for high power and compact units has to some extent been superseded by the additional need for high stability low order mode output beams required for precision cutting and deep penetration welding. The fast axial flow laser has more recently been identified as being able to meet these more stringent requirements and research and development work in this field has been stimulated. This new initiative has resulted in the development of a number of new fast axial flow lasers about which there have been little or no published work reported in the scientific journals because of the commercial sensitivity of the work. The organisations developing these units include Ferranti (UK), The Welding Institute (UK), Cilas-Alcatel (Belgium), Trumpf (Germany) and the Compagnie Generale d'Electricite (France). The work reported here, however, does give a representative view of the fast axial flow lasers available commercially, many of which use the same basic technology as the Control 2 kW laser.
3.6 TRANSVERSE FLOW LASERS

Transverse flow lasers represent the third type of CO₂ laser introduced in Section 3.1. Although they are not specifically the subject of the thesis they do however represent an important area of high power CO₂ laser development incorporating many useful techniques and solutions to problems applicable to the design of fast axial flow lasers. For this reason literature published on the transverse flow laser has been included in this review section.

The transverse flow laser (Fig 3.1(c)) uses a high velocity gas flow perpendicular to the electric discharge and optical axis in contrast to the fast axial flow laser (Fig 3.1(b)) in which all three axes are parallel. A characteristic of this type of laser is the small electrode separation resulting in short glow discharges (typically 30-50 mm long) which are subjected to high velocity gas flows (typically 40-100 m/s) across the discharge region. The transverse flow of gas across the discharge can lead to very short gas dwell times (<1 ms) and correspondingly high electrical power densities (Weigand and Nighan 1975). The short discharges result in lower discharge voltages (>2 kV) and higher total currents (up to 20 A) than the fast axial flow laser. The low discharge voltages compared with the fast axial flow laser (>15 kV) reduce the maximum electrical to optical efficiency because of the fall voltage (which does not contribute to laser action) representing a higher proportion of the total discharge voltage which limits the electrical to optical efficiency to typically 6-8% in commercial lasers. These efficiencies are substantially lower than those reported previously for fast axial flow lasers of similar laser power outputs. Larger electrode separation and higher gas velocities would increase the total discharge voltage and hence the
electrical to optical efficiency but are not practical because of the onset of discharge instabilities. The effect of these instabilities can be reduced by using gas flow conditioning techniques.

The transverse flow arrangement usually incorporates a large cross-sectional area rectangular discharge region which offers little resistance to the flowing gas which dispenses with the need for high pressure positive displacement Roots blowers and enables high speed vane axial fans to be used to circulate the laser gas. This can have advantages in terms of capital cost, gas contamination and overall equipment size, but also means that the discharge region, and the gas recirculating fan and flow path are an integral part of the laser cavity.

The first transverse flow laser with a closed-loop gas recirculating system was reported by Tiffany et al (1969) and Targ and Tiffany (1969). The laser developed up to 1100 W from a 1 m active length of discharge at an electrical to optical efficiency of 8%. The 40 mm diameter multimode beam was coupled from the 1 m single path oscillator through a 35% transmitting germanium output window. The dwell time of the gas in the discharge region was 1 ms for a gas flow velocity of only 35 m/s demonstrating that the transverse flow laser could potentially be operated at high electrical power densities. The electrical power loading of the gas was only 204 kW/kg/s indicating the possibility of increasing the output power still further. Targ et al (1969) also reported a higher value of saturation intensity (246 W/cm²) than had been observed in slow flow lasers. It was suggested that the rapid flow of gas into and out of the laser cavity was a major reason for the higher saturation intensity since the rate at which molecules were transported through the laser cavity
(about 1 ms) was comparable with the upper level relaxation time. Thus in fast flow convection lasers, the saturation intensity is not only a function of the upper state relaxation time but is also dependent on the gas flow velocity of the lasing medium.

A transverse flow electric discharge mixing laser described by Brown (1970) is shown in Fig 3.9 in which the He and N₂ is pre-excited in a discharge tube which is external to the laser cavity. The stream of He and N₂ is excited in an abnormal glow discharge to generate vibrationally excited N₂ which is then rapidly mixed with cold CO₂ injected into the laser channel to provide the necessary population inversion by resonant energy transfer from the N₂(n=1) into the upper laser level (001) of CO₂. Because the excited N₂ molecule has a slow decay rate associated with the transition from the vibrational to the translational mode, there is little decay of the N₂(n=1) molecules during the transit time through the laser channel (2 ms). The laser developed up to 900 W laser output at a gas pressure of 64 mb, gas flow velocity of 148 m/s and an electrical to optical efficiency of 11%. The system is however limited to an open cycle mode of operation because of the need for separate gas supplies and therefore has a high gas consumption.

Hill (1971) reported the application of aerodynamic techniques to produce a large volume uniform glow discharge at electrical power loadings of up to 595 kW/kg/s at gas pressures in the range 40-200 mb and gas flow rates of up to 13.2 m³/s (corresponding to a mass flow rate of 0.33 kg/s). The laser amplifier (Fig 3.10) incorporated a number of individually stabilised anodes positioned immediately downstream of an array of rods used to shed vortices around each of the anodes. The vortices caused rapid diffusion of the plasma tending to
Fig 3.9 Transverse flow electric discharge mixing laser
(after Brown 1970)

Fig 3.10 Aerodynamic transverse flow laser (after Hill 1971)
minimise any thermal gradients and interelectrode breakdown. An array of insulating nozzles was placed downstream of the anodes further enhancing the mixing by driving the gas flow supersonic, then shocking it back to subsonic. Downstream of the nozzles the individual plasmas merged to produce a single, uniform, large volume plasma with stability such that the input power could be increased with gas pressure (or mass flow rate). Following the shock wave developed in the nozzles the discharge remained diffuse for gas dwell times of up to 2 ms without the need for any further turbulence in the discharge region. The shock waves developed in the nozzles corresponded to a gas velocity between Mach 1.5-1.7 and were located near to the anode arrays just upstream. Careful design of the supersonic nozzles enabled a high degree of pressure recovery across the array with a total pressure loss of only 15% of the entrance pressure making the flow conditioning technique efficient but probably outside the differential pressure range of vane axial fans or turbopumps (typically $\Delta P/P < 1\%$ Buczek et al 1970).

Individual anodes were electrically stabilised by 20 k ohm resistors and operated up to a maximum current of 133 mA per anode. A maximum electrical power of 100 kW was coupled into the discharge which had a volume of 43 litres. The 17 pass power amplifier developed 19 kW CW single mode laser output when pumped with a 120 W single mode laser oscillator. The effect of introducing a partial pressure of 1.3 mb of air to the gas recirculating system was catastrophic collapse of the discharge to an arc under all conditions of gas flow and electrical power input.

A magnetically stabilised transverse flow laser was proposed by Buczek et al 1970 (Fig 3.11). Collisions between the flowing neutral molecules and the ionised species in the electric discharge cause the discharge to move downstream in the direction of the flowing gas. A
transverse magnetic field (B) was used to interact with the charged particle drift velocity (U) to develop a stabilising force $U \times B$ which maintained the electric discharge on the optical axis. Laser output powers of up to 540 W were obtained from the 1 m active region at a gas pressure of 33 mb, flow velocity of 50 m/s and magnetic flux density of 0.0275 T. A maximum electrical to optical efficiency of 10% was obtained at a discharge current of 340 mA. The magnetic field was used solely to maintain the discharge on the optical axis and was not used to contribute towards improving the uniformity of the discharge. The equipment was therefore limited to low discharge currents (<340 mA) and small electrode separations (<20 mm).

Eckbreth and Davies (1972a) reported on an open cycle transverse flow convection laser amplifier using flow conditioning techniques to increase the electrical power density and stability of the electric discharge. A number of flow conditioning methods were applied including a range of vortex generators and rectangular apertures placed near the upstream tungsten cathode pins. Each cathode pin was separately stabilised through resistors to spread the discharge across the 600 mm x 25 mm channel. The laser is shown schematically in Fig 3.12. The laser although used in the open cycle mode was designed for minimum pressure drop for potential closed loop operation, the maximum pressure ratio across the channel was 1.24. Turbulence in the discharge region was found to improve the stability of the discharge and enabled the power in the discharge to be raised from 11 to 16 kW. The turbulence was introduced just upstream of the discharge region by using vortex generators placed about the periphery of the channel or by means of a rectangular aperture of the same width as the channel but of smaller height which modified the gas flow into the discharge. The mixture of gases used was varied and higher proportions of helium were
Fig 3.11 Magnetically stabilised transverse flow laser (after Buczek et al 1970)

Fig 3.12 Schematic of transverse flow laser amplifier (after Eckbreth and Davies 1972 a)
found to greatly improve the discharge stability and enable operation at higher pressure to be achieved. Although the higher helium content allowed operation at higher pressures, the molecular weight was reduced and the small signal gain is reduced. The higher specific heat capacity of the helium does lead to lower discharge temperatures and can therefore lead to improved electrical to optical efficiencies. No such investigations were made by the authors. A laser output power of 2050 W was achieved from the amplifier for a 225 W laser input and a discharge power of 19 kW. The electrical to optical efficiency was 9.6% at a gas pressure of 53 mb and mass flow rate of 0.045 kg/s.

Eckbreth and Owen (1972) employed four adjustable baffles upstream of the cathodes to modify the turbulence level and velocity profile in the discharge zone (Fig 3.13). The discharge behaviour was found to be extremely sensitive to the angular position of the baffles. These were later perforated (10% porous) to reduce the sensitivity of the discharge to the angular position of the baffles. The authors identified the problems of creating non-uniform turbulence levels and skewed velocity distributions by inserting electrodes into the gas flow and proposed the use of baffles to optimise the gas flow in the discharge region. The time averaged turbulence level was determined by hot-wire anemometry for the optimised and detuned conditions varying only slightly around the 4% level. The velocity distribution across the channel was found to vary by up to 12% for the detuned conditions and by only 4% for the optimised conditions, indicating that a uniform velocity distribution is extremely important in maintaining discharge stability. It was possible to increase the input power levels to the discharge by up to 50% when the gas flow was optimised. The highest power loading of the gas achieved was 455 kW/kg/s under open cycle conditions and 390 kW/kg/s under closed cycle conditions, the
difference being attributable to the recirculation of unwanted dissociative and contaminant species (Bletzinger et al 1975).

The use of an auxiliary radio frequency (rf) power source was investigated by Brown and Davies (1972) and Eckbreth and Davies (1972b) using the same laser amplifier with adjustable baffles described above (Eckbreth and Davies 1972a). A 13.7 MHz rf power supply was used to supply two copper electrodes on the outside of the laser channel to capacitively couple rf power into the electric discharge (Fig 3.14). The application of the rf auxiliary power to the dc discharge, the stability and uniformity of the discharge was greatly enhanced raising the closed cycle electrical power loading from 460 kW/kg/s to nearly 780 kW/kg/s. Increases in the rf power reduced the sensitivity of the discharge to the angular position of the baffles. Up to 50% of the total discharge power applied was rf and as the rf power was increased, the dc power peaked and then decreased. This could have been due to thermal loading of the gas or increased ionisation resulting in a more rapid decrease in electric field strength than the increase in current density due to electrical conductivity variations with temperature. The rf field was found to have no effect unless the field was applied perpendicularly to the electric field of the dc discharge. It was proposed that the enhancement of the discharge performance was due to the rotation of the rf current density vector interacting with the dc current vector resulting in a time averaged suppression of discharge instabilities. Brown and Davies (1972) reported a maximum laser output of 27.2 kW at an electrical to optical efficiency of 17.2% for a laser input power of 150 W, a dc discharge power of 100 kW and an rf power of 60 kW. The application of rf power to the discharge was found to improve the discharge stability and uniformity beyond that which has yet been reported using flow conditioning techniques alone.
Fig 3.13 Schematic of baffle-electrode geometry for a transverse flow laser (Eckbreth and Owen 1972)

Fig 3.14 Laser channel arrangement with rf assisted electrodes (after Brown and Davies 1972)
Lancashire et al (1977) described the NASA high power CO$_2$ laser designed to generate up to 70 kW of laser output power. The transverse flow laser incorporated a pin to plane electrode system for a self-sustained dc discharge as well as an electron beam to preionise the discharge. The use of an electron beam enables the degree of ionisation of the discharge and hence the value of E/N to be varied independently of the dc discharge conditions and gas conditions. Varying the electron beam current enables the value of E/N to be optimised for the most efficient excitation of the laser gas (Fig 3.15 (a) and (b). The laser gas was recirculated at mass flow rates of up to 1.2 kg/s by a centrifugal blower with a 2.1 m diameter impellor driven by a 250 hp variable speed drive. The laser was operated in the pressure range of 133-1024 mb with transverse gas velocities of up to 150 m/s. The laser was also designed using high vacuum techniques to minimise atmospheric contamination and to investigate the effects of contamination due to plasma-induced chemical reactions on closed cycle operation. A combination of vacuum pumps enabled the laser to be evacuated to $10^{-6}$ mb to reduce the effect of residual gases on the laser performance. The maximum laser output power reported was 5.9 kW at an electrical to optical efficiency of 7%, a gas pressure of 190 mb and a specific laser power of only 8.2 kW/kg/s.

Hoag et al (1974) describe a 10 kW electron beam sustained laser in which the electron beam, gas flow and optical axes are all orthogonal to each other (Fig 3.16). The large cross-sectional area beam passes through a metal foil (<0.025 mm thick) and through a porous sustainer electrode into the discharge region where it provides a controllable secondary electron population. These secondary electrons are then heated to the optimum temperature $T_e$ by applying a suitable dc
Fig 3.15 The NASA high power CO\textsubscript{2} laser (after Lancashire et al 1975)

(a) pin to plane self-sustained configuration

(b) electron beam sustained configuration

Fig 3.16 The AVCO HPL-10 electron beam sustained 10 kW CO\textsubscript{2} laser (after Hoag et al 1974)
electric field to maintain an optimum value of $E/N$. A near optimum value of $E/N$ of $1.2 \times 10^{-16}$ V.cm$^{-2}$ (Lowke et al 1973) was maintained using this technique by adjusting the dc potential difference between the two sustainer electrodes. A maximum laser output of 17 kW was extracted from the laser through a high velocity gas flow aerodynamic output window.

Tanaka et al (1985) report on a high frequency (100 kHz) silent discharge technique used in a number of transverse flow CO$_2$ lasers marketed by Mitsubishi. A transistor inverter power supply was used to supply two water-cooled electrodes made of rectangular glass coated iron tubes (40 mm x 40 mm x 1500 mm) with a sinusoidal output at frequencies between 2-100 kHz - no dc supply is used. A gas mixture containing CO (to control the rate of gas dissociation within the discharge) flowed through the 40 mm gap between the glass-coated electrodes at gas velocities up to 70 m/s and gas pressures of up to 130 mb (Fig 3.17). The frequency of excitation was selected on the basis of a conduction model that suggested that positive ions in the discharge were trapped in the discharge region by the rapidly varying electric field. The drift velocity of an ion under these conditions was 600 m/s while that of an electron was about two orders of magnitude higher. The drift time $t$ of an ion across the 40 mm gap was about 70 $\mu$s. At a supply frequency of $f=100$ kHz a condition where $t>1/2f$ is established and the discharge gap maintains conduction continuously due to the presence of ions. When $f=2$ kHz, $t<1/2f$ and the discharge gap ceases to conduct during part of the alternating cycle and the discharge becomes unstable. The lasers operate on a total gas exchange principle whereby the lasers run for up to 100 hours before being shut-down and the recirculating gas is then replaced with fresh gas. Laser output powers from 500 W to 5 kW have been manufactured using the
silent discharge technique.

Tabata et al (1984) describes another Japanese development using a high frequency preionisation technique combined with a dc discharge. The Silent Discharge Assisted Glow Excitation (SAGE) uses a 'silent discharge' electrode supplied with a 25 kHz high voltage, located upstream in the 40 m/s gas flow to provide approximately 5% of the total discharge energy preionisation (Fig 3.18). The bulk of the discharge power is supplied from a dc power supply via a linear array of molybdenum pin cathodes and a planar copper anode. Laser output powers of up to 20 kW have been achieved at electrical to optical efficiencies of up to 13%. The lasers, marketed by Mitsubishi also operate on the total gas exchange principle (every 100 hours) and to maintain a constant power output as the laser gas degrades with time, the input current to the discharge is controlled by feedback from the laser output power.

The Ferranti CL5 kW laser was developed by the Culham Laboratories (UKAEA) and uses two pairs of distributed electrodes forming two cavities 50 mm x 50 mm x 1000 mm placed optically in series (Fig 3.19). Each set of electrodes operates at a dc discharge current of 14 A and a voltage of 2 kV giving an electrical to optical efficiency of 9%. The equivalent laser output power per unit length of discharge is 2.5 kW/m. The laser gas is recirculated by a two stage high-frequency (12,000 rpm) vane axial fan at a flow rate of 5 m³/s at a gas pressure of 66 mb giving a gas flow velocity of 50 m/s through the discharge region. The 40 mm diameter beam is extracted from the unstable resonator through either a ZnSe or a differentially pumped aerodynamic output window. The discharges have to be operated in the normal glow discharge regime to maintain acceptably low arcing rates. Gas is added to the system
Fig 3.17 Silent discharge electrode arrangement (Tanaka et al 1985)

Fig 3.18 Silent discharge assisted glow excitation (SAGE) electrode configuration (Tabata et al 1984)
Fig 3.19 The Ferranti CL5 5 kW transverse flow laser
continuously at a flow rate of 2.5 l/min at atmospheric pressure rather than using a catalytic gas reconstitutor. A 10 kW version of the above laser is also available, the CL10, which is simply two CL5 lasers operating side by side but with the optical path through the discharge region connected in series. The largest and most powerful laser built at Culham had an output power of 20 kW and was also a multifolded version of the CL5 laser.

A high power pulser-sustained CW CO₂ laser is described by Nam et al (1979) and Segiun et al (1979) using a technique known as PIE (or Photo-ionised Impulse-enhanced Electrical) excitation (Fig 3.20). A high pulsed voltage is applied to the UV-source electrodes to produce a corona discharge at the tips of the electrodes where the electric field reaches high values and causes photo-ionisation of gas molecules in the interelectrode space. The high voltage impulse accelerates the photo-electrons causing more ionisation and increases the electron density. The high voltage impulses are repeated at a frequency of 5 kHz and maintain the electron density creating a stable large volume uniform plasma. A direct current from a separate 240 kW thyristor controlled power supply is superimposed on the discharge to pump the gas molecules. Typically less than 1% of the power is supplied by the high frequency component of current. The laser is operated at a gas pressure of 66 mb and the gas recirculated by six high speed fans at a flow rate of 23 m³/s. The anode is made up of an array of profiled water-cooled copper tubes and the cathodes consist of an array of pins individually stabilised and cooled by a circulating flow of potassium carbonate electrolyte. A uniform plasma of up to 80 litres in volume has been operated developing a laser output power of 20 kW through a ZnSe output window at an electrical to optical efficiency of 8%. The TEM₀₁ annular output beam produces a uniform temperature distribution
across the centre portions of the ZnSe output window which is water-cooled at the edges. The beam profile leads to efficient cooling of the window in contrast to for example a Gaussian mode in which the highest thermal loading occurs at the centre of the window, farthest from the water cooling. The laser can only be operated for five minutes at a time on a 50% duty cycle due to limitations on the cooling system.

Spectra-Physics produce a range of high power transverse flow lasers (1.5-5 kW) based on the work of Tiffany et al (1969). The Spectra 825 2.5 kW laser (Fig 3.21) uses a dc separately stabilised segmented anode and a continuous tubular cathode. The gas is recirculated through the laser by a tangential blower and directed around the anodes by aerodynamic vanes into the discharge region. The laser develops an output power of 2.5 kW at a discharge current of 14.2 A and a discharge voltage of 1420 V which corresponds to an electrical to optical efficiency of 12.4%. A closed loop control circuit monitors the laser output power via a 99.5% rear mirror and regulates the discharge current to maintain the output power within ± 1% at rated power. The output power is continuously variable in the range 400-2500 W. The optical path passes through the discharge region five times, each of the folding optics being mounted on a thermally stable invar structure which is contained within a vessel sealed to the atmosphere. This vessel eliminates the mechanical stresses caused by differential gas pressures across the resonator optics and reduces the problems of vacuum sealing the laser. The optics are factory set, the only adjustment being on the output window which is fitted with two stepper motors for remote tuning of the laser.

The Falcon 800 developed by Laser Corporation of America utilises
Fig 3.20 The PIE 20 kW transverse flow laser (Seguin et al. 1979)

Fig 3.21 Spectra Physics 825 2.5 kW transverse flow laser
an rf excited transverse flow discharge and produces 1000 W of laser output from a laser head measuring 1040 mm x 400 mm diameter and weighing 108 kg. The laser head contains the multipass stable resonator, discharge assembly, heat exchanger and the recirculating squirrel-cage blower and is connected to a control cabinet by a 6 m flexible umbilical carrying the cooling water, gas and electrical supply lines. The laser develops 2.3 kW/m of discharge and uses capacitive ballasting of the pin electrode structure which reduces the heat dissipation with the laser head. The gas consumption of the laser is unusually high at 4.2 l/min for a 1 kW laser when compared with for example the Spectra Physics 825 laser which was only 1.4 l/min for 2.5 kW laser output power. Few details are available in the literature about the exact excitation conditions, cavity geometry and gas flow paths.

Tables 3.1 and 3.2 summarise the performance characteristics of the fast axial flow and transverse flow lasers reviewed in this chapter.
<table>
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<tr>
<th>Power output (W)</th>
<th>Power per unit length discharge (kW/m)</th>
<th>Electrical to optical efficiency (%)</th>
<th>Laser power per unit volume of discharge (mJ/mm³)</th>
<th>Electrical power loading of gas (kW/kg/s)</th>
<th>Output power density (W/cm²)</th>
<th>Tube dia (mm)</th>
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Table 3.1 Fast axial flow lasers.
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<th>Power output (W)</th>
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<th>Laser power per unit volume of discharge (mW/mm³)</th>
<th>Electrical power loading of gas (kW/kg/s)</th>
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Tiffany et al 1969
Brown 1970
Hill 1971
Buczek et al 1970
Eckbreth and Davies 1972
Eckbreth and Owen 1972
Brown and Davies 1972
Lancashire et al 1974
Hoag et al 1974
Tanaka et al 1985
Tabata et al 1984
Ferranti
Seguin et al 1979
Spectra Physics
Laser Corporation of America

Table 3.2 Transverse flow lasers
4.1 INTRODUCTION TO ELECTRIC DISCHARGES

The term electric discharge is used to describe the flow of electric current through a gaseous medium. To develop a conducting path for the passage of an electric current some of the gas particles must be ionised and there should exist an electric field to accelerate the charged particles between the electrodes. In the process, electrons collide with free gas molecules giving rise to elastic collisions, excitation, ionisation and sometimes the formation of negative ions. Radiation in the form of emitted photons produced and give rise to the luminous nature of electric discharges. The positive ions produced from these collisions will be accelerated by the applied electric field and move toward the cathode. Bombardment of the cathode by positive ions can release secondary electrons from the cathode surface which further contribute to the ionisation of the gas. If sufficient electrons are released to maintain the electric current the discharge is described as self-sustaining. The positive ions will also recombine with electrons to form neutral atoms. These interactions between the ions, electrons and electrodes result in the release of thermal energy which raises the temperature of the gas.

Electric discharges can be operated over a wide range of atmospheres, gas pressures and discharge currents. They may be steady state processes or transients of very short duration. The characteristics of an electric discharge between two electrodes depend upon the nature of the gas, the electrode materials, the nature of the applied voltage and the constants of the external circuit.
The voltage current characteristics of an electric discharge may be determined using a circuit such as that shown in Fig 4.1.

(a) the Townsend or dark discharge \((I < 10^{-6} \text{ A})\)

(b) the glow discharge \((10^{-6} \text{ A} < I < 0.1 \text{ A})\)

(c) the arc discharge \((I > 0.1 \text{ A})\).

Variations in the gas pressure can lead to exceptions to the above classification such as low pressure glow discharges operating at several hundred amps in glow discharge nitriding processes (Edenhoffer 1974).
The Townsend discharge is characterised by a very low current; it is invisible because the density of excited species which emit visible light is correspondingly small. The discharge is not self-sustaining and so requires an external source of ionising radiation to produce electrons either directly in the gas or from the cathode. Sources of preionisation include radio frequency discharges, ultraviolet radiation, electron beams and X-rays.

Fig 4.2 The generalised voltage current characteristic of an electric discharge.

If the supply voltage $V_o$ is increased or the stabilising resistance $R_s$ is reduced, the current will at some point increase
abruptly by several orders of magnitude. This is the breakdown point and depends on the gas pressure, the type of gas and the separation and shape of the electrodes. Once breakdown has occurred the discharge can become self-sustaining provided the diffusion and recombination rates do not exceed the electron production rate. The discharge will take the form of a glow or an arc, depending on the circuit and gas conditions. The discharges are both luminous, the emitted spectra depending on the degree of ionisation and the type of gas.

If the gas pressure is below 1 mb a glow discharge tends to form on breakdown, the gas then emits a diffuse glow of characteristic colour with several distinct regions and passes a current which is of the order of milliamps to one amp with a potential difference ranging from several hundred volts to many kilovolts. If the pressure on breakdown is tens of millibar and the resistance of the external circuit is low, then breakdown is likely to result in the formation of an arc discharge. The arc discharge is characterised by a smaller diameter column and more intense visible radiation than the glow discharge and the discharge current is usually in the range of several amps to many kiloamps with a relatively lower voltage gradient.

It is possible to operate arc discharges at low gas pressures, such as in the mercury arc rectifier or vacuum arc furnace (Guile 1971). It is also possible to operate glow discharges at pressures above atmospheric pressure at currents of several amps (Fan 1939) but it is found that the glow discharge tends to an arc if either the gas pressure or current or both are increased. This change is called the glow to arc transition and is usually accompanied by an abrupt increase in discharge current and fall in discharge voltage.
4.2 THE GLOW DISCHARGE

The glow discharge derives its name from a luminous zone which develops near the cathode which is separated from the cathode surface by a dark space. When a direct current glow discharge is established in a long cylindrical tube filled with gas at a pressure of between 0.1-1 mb the visible light from the discharge is distributed between the electrodes as shown schematically in Fig 4.3(a).

The dark spaces are not totally devoid of light but are only dark relative to the bright regions where ionisation and excitation processes are more active Fig 4.3(b). If the gas pressure is reduced at a constant electrode separation, the negative glow and the Faraday dark space appear to expand at the expense of the positive column until at sufficiently low gas pressure, the positive column disappears completely. If the gas pressure is increased above about 1 mb at constant electrode separation, the negative regions of the glow discharge contract toward the cathode. Above about 10 mb only the Faraday dark space is clearly visible. The positive column fills the remainder of the gap, but with a reduced column diameter at higher pressures because of the larger hydrostatic forces acting upon it. If the electrodes are moved together at a constant gas pressure and discharge current, the region from the cathode up to and including the Faraday dark space remains unchanged in length, whereas the positive column decreases in length and finally disappears. From the above observations it appears that the regions at and near the cathode are essential to sustaining the glow discharge and that the positive column merely acts as a conducting path for the current.

The distribution of the applied voltage along the glow discharge
Fig 4.3 Characteristics of a glow discharge showing the distribution of various parameters (after Von Engel 1955)
is shown in Fig 4.3(c). A large proportion of the voltage is required for the cathode fall region and in particular the cathode dark space where the electric field strength is high as shown in Fig 4.3(d). The field strength decreases towards the negative glow and after passing through a minimum value in the Faraday dark space stays constant throughout the positive column and only rises again at the anode.

When the discharge current is low (region CD in Fig 4.2) the cathode surface is not completely covered by the negative glow and the current density at the cathode is constant and independent of the discharge current. Under this condition the cathode fall voltage is also constant and the discharge is termed a normal glow discharge. When the discharge current is increased to a certain critical value $I_a$ where the cathode surface becomes completely covered with the negative glow, both the cathode current density $J_c$ and the fall voltage rise simultaneously. This region of the characteristic is termed the abnormal glow discharge (region DE in Fig 4.2).

The conduction of current through a glow discharge occurs by the movement of electrons and positive ions between the anode and cathode. The discharge current is mainly electronic rather than ionic because of the greater mobility of the electrons. The net charge density and the current density distribution along the discharge are shown in Fig 4.3(e) and (f) respectively. At the cathode there is a net negative charge produced as a result of the electrons emitted from the cathode surface. Since the initial velocities of these electrons are low, the electron current density in this region is relatively small and the discharge current is carried almost entirely by positive ions arriving at the cathode from the cathode dark space. The cathode dark space is a region of high positive ion density. This high density of slow
moving positive ions contributes to the high value of cathode fall voltage. On the anode side of the cathode dark space, most of the discharge current is carried by the electrons that have now been accelerated away from the negative polarity electrode. The electron concentration increases to such an extent that in the negative glow the net charge density is nearly zero and the potential reaches a high value with a very low field. In the Faraday dark space the field again rises resulting in further acceleration of the electrons. The positive column is a region of almost equal concentration of positive ions and electrons and is characterised by a relatively low voltage gradient. At the anode, there is a decrease in the positive ion density and an increase in the electron density such that the current at the anode is purely electronic. There is also an increase in both the electric field strength and the potential at this point.

4.3 THE CATHODE

The cathode region extends from the cathode to the anode side of the cathode dark space and is denoted $d_c$. The voltage across this distance $d_c$ is called the cathode fall potential or cathode drop $V_c$. The magnitude of the cathode fall potential depends mainly upon a combination of the gas type and cathode material, varying only slightly with gas pressure, electrode geometry and the discharge current. The cathode fall voltage can be as low as 64 V for a potassium electrode in argon and as high as 490 V for a platinum cathode in carbon monoxide. The glow discharge is characterised by a large cathode fall voltage, typically 300 V for a molecular gas. Table 4.1 summarises the approximate values of the normal cathode fall voltage for different combinations of electrode and gas.
The cathode fall voltage increases nearly linearly with the work function of the cathode material. This is reasonable since the maintenance of the self-sustaining discharge depends on the emission of electrons from the cathode. The various emission processes are discussed later. The normal cathode fall potential decreases with the ionisation potential of the gas since a greater number of the gas molecules can be ionised by more lower energy electrons and so contribute to conduction across the cathode fall region. For a glow discharge to be self-sustaining the cathode fall potential must be such that each electron leaving the cathode establishes the necessary ionisation of the gas molecule for its replacement by positive ion bombardment of the cathode. The presence of low work function impurities in the cathode will also lower the cathode fall voltage because of the greater ease of displacing electrons from the cathode.

The use of modern dispenser type cathodes utilising barium and caesium compounds (Cronin 1978) to provide large numbers of electrons and very low cathode fall voltages is prohibited in CO₂ gas lasers.
because of the presence of dissociated oxygen, high gas pressures and the potential contamination of the lasing medium by sputtered electrode material.

The current density at a plain cathode \( J_n \), which in the normal glow discharge does not vary with discharge current, is found to vary as \( P^2 \) if the pressure is below approximately 2 mb (Von Engel and Steenbeck 1934). If the pressure is above this, \( J_n \) increases less rapidly and is found to vary as \( P^{4/3} \) (Seeliger and Reger 1927). For cylindrical electrodes the current density \( J_n \) varies directly with the gas pressure (Howatson 1976).

The cathode glow can take on three different characteristics; the first cathode layer, the cathode glow and the cathode light. The first cathode layer is a low voltage, low pressure phenomenon associated with the loss of electron energy to gas excitation. At higher pressures (typically > 1 mb) the cathode surface is covered with the negative glow. This results from the loss of excitation energy of the positive ions on neutralisation when hitting the cathode surface. When the cathode is covered with a thin metallic or semi-insulating oxide layer, atoms of the layer may be sputtered off and the excitation of these gives rise to the cathode light which ceases to exist after an initial conditioning period where surface irregularities and oxide layers are removed (Brown 1966).

**Cathode Sputtering**

The cathode surface in a glow discharge is subjected to bombardment by positive ions which causes a continual disintegration of the cathode surface by sputtering. The particles lost from the
cathode are then re-deposited on other surfaces within the vacuum system. In gas discharge lasers this process is extremely detrimental to the long term operation of the laser because of the gradual degradation of the laser optics by deposited material and contamination of the lasing medium by metal ions. At high cathode fall voltages (>200 V) the mass of sputtered material is proportional to the discharge current. Sputtering increases with the mass and the rate at which the positive ions arrive at the cathode surface. Table 4.2 summarises the rate of sputtering (×10^-9 kg/A/s) for a number of metals in hydrogen. The cathode fall voltage was maintained at 850 V throughout.

<table>
<thead>
<tr>
<th>Mg</th>
<th>Cr</th>
<th>Al</th>
<th>Mn</th>
<th>W</th>
<th>Ni</th>
<th>Fe</th>
<th>Cu</th>
<th>Zn</th>
<th>Au</th>
<th>Ag</th>
</tr>
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<tr>
<td>2.5</td>
<td>7.8</td>
<td>8</td>
<td>11</td>
<td>16</td>
<td>18</td>
<td>19</td>
<td>84</td>
<td>95</td>
<td>130</td>
<td>205</td>
</tr>
</tbody>
</table>

Table 4.2 Summary of sputtering rates for various metals in an atmosphere of hydrogen (Cobine 1958).

From these figures it is evident that copper, a material commonly used as a watercooled cathode in lasers (Ivanchenko et al 1969) is an entirely inappropriate material to use because of its high sputtering rate. A more suitable material to use would be aluminium which has a sputtering rate approximately one tenth that of copper and which has good machining properties. A pure aluminium such as that used for high current bus-bars is more suitable than many of the heat treated aluminium alloys which contain significant percentages of copper, zinc and manganese, all of which have higher sputtering rates.
4.4 THE POSITIVE COLUMN

The positive column is bounded at one end by the Faraday dark space and at the other by the anode glow and is so called because it connects the negative zones to the anode. The positive column is an example of a plasma, that is an ionised gas having a zero net space charge. The plasma therefore has approximately equal numbers of electrons and positive ions, each with their own velocity distribution and characteristic temperature. The gas temperature of the column is much lower than that of a constricted arc (about 6000 K on the axis) and is typically less than 500 °C. In high power gas lasers the average gas temperature is maintained below 270 °C by using high gas flow rates to convectively remove the heat in the gas at high specific electrical power loadings (500-700 kW/kg/s). The low temperature characteristic of the glow discharge indicates that thermal ionisation cannot be a factor in the conduction mechanism of the column of the glow discharge. The electron concentration is of the order of \(10^5 \text{ mm}^{-3}\). The temperature of the positive ions is slightly higher than the gas temperature and the electron temperature is very high (typically \(> 1 \text{ eV}\)). This high electron temperature is why the glow discharge is suitable for exciting molecules for laser action and also for low pressure chemical synthesis where conventional thermal processes would destroy the reactants or final product (Suhr 1973, Harry and Evans 1986). The current through the positive column is carried almost completely by electrons rather than positive ions because of the much greater mobility and drift velocity of the electrons. It thus appears that since an equal number of charges of both polarity are produced in the column, more electrons than ions would leave the column. The result would be an accumulation of positive ions increasing with time. This is not the case. When the
transport of charge along the column is considered the ends have to be excluded. There is a constant influx of electrons from the Faraday dark space which are then removed by the anode at the positive end of the column. There is also a constant flow of positive ions down the column as a result of ionisation in the anode region which are driven into the positive column by the repelling positive field of the anode (Von Engel 1965).

The voltage gradient along the positive column is a function of the discharge tube radius, the type of gas, the gas pressure and velocity and the discharge current. As the tube radius is decreased the voltage gradient rises rapidly because of the greatly increased loss of ions by diffusion to the walls. This diffusion increases the recombination rate of ions and electrons which requires an increase in the ionisation processes established by the electric field if the same discharge current is to be maintained. A rise in gas pressure increases the voltage gradient since the hydrostatic forces acting on the discharge column tend to constrict the discharge and so decrease the mean free paths of the ions which increases the recombination losses through collision processes. The voltage gradient is of the order of 0.1 V/mm under zero flow conditions with a typical CO₂ laser gas at 40 mb. At high flow conditions (> 0.02 kg/s) with all other parameters held constant, the voltage gradient can rise to approximately 20 V/mm. This wide variation in the value of electric field strength makes the choice of operating conditions for an electric discharge used to selectively excite laser transitions particularly important if efficient laser excitation is to be achieved. The ratios E/P and E/N are used to identify the optimum conditions for efficient pumping of the laser medium and values of the order of E/P = 0.38 V/mm.mb and E/N = 1.2 x 10⁻¹⁶ V.cm² are typical
for high power CO₂ lasers. These values correspond to an average electron temperature of approximately 1 eV.

The colour of the positive column is not usually the same as that of the negative glow, its spectrum shows only arc lines, while that of the negative glow shows some of the spark lines. The colour of the positive column is sensitive to the type of gas, the discharge current and the presence of very small amounts of impurities (Thomson and Thomson 1933). The pink positive column associated with the helium present in CO₂ laser discharges can turn to a bluish-white colour in the presence of air introduced into the gas recirculating system.

In a limited tube geometry there is a relationship between the tube radius and the electron mean free path within the gas. For tubes of up to approximately 10 mm with gas pressures of less than 10⁻² mb (when the electron mean free path is much larger than the tube radius), space charge and diffusion effects are small while at higher gas pressures of the order of 15 mb (the electron mean free path is much less than the tube radius), the current density can be high enough to introduce complex ionisation processes, such as cumulative and thermal ionisation and the column may take the form of narrow, filamentary arcs (Llewellyn-Jones 1966). This latter condition can often exist in high power CO₂ lasers.

4.5 THE ANODE

The anode is positioned at one end of the positive column attracting electrons and repelling positive ions, resulting in a negative space charge immediately in front of it. Since no positive
ions are emitted from the anode the entire current at the anode surface is electronic. Any positive ions which may be formed in the gas by the incoming electrons attracted to the anode are accelerated away from the anode surface. As a consequence of this negative space charge there is a potential drop known as the anode fall voltage which occurs over a very short distance (typically of the order of one mean free path of an electron Brown 1965). An electron emerging from the positive column enters the anode fall region with a small initial energy and is then accelerated towards the anode. After it has crossed the anode dark space it acquires sufficient energy to ionise the gas in front of the anode and the anode becomes covered with a luminous sheath - the anode glow.

When there is no positive column such as in a very short discharge tube, the anode fall potential can be very small because ions and electrons diffuse together toward the anode from the negative glow in such a way that charge neutrality is maintained (Cobine 1958). When long discharge tubes are considered and a fully developed positive column exists, ions and electrons do not diffuse in this manner and charge neutrality cannot be maintained in the anode region. Electrons flowing across the negative space charge region must generate positive ions at the same rate as they flow out of the column into the Faraday dark space. If this condition is not met, insufficient positive ions are produced at the anode end of the column and the negative space charge region grows so that the anode fall voltage rises and more ionisation occurs until enough positive ions are generated to correct the shortage.
4.6 THE GLOW TO ARC TRANSITION

The glow to arc transition can be represented on the generalised voltage current characteristic of an electric discharge (Fig 4.2) as a region (EF) of instability between the stable abnormal glow and the stable arc discharge regions (region FG). The discharge current at which the glow to arc transition occurs places an upper limit on the electrical power input to a glow discharge. At the high electrical power loadings required in multikilowatt CO₂ lasers (typically greater than 300 kW/kg/s) the glow to arc transition represents a severe problem in achieving reliable, stable operation of the laser without the formation of arc discharges which cause a reduction and sometimes catastrophic loss of laser power output. The arc discharge is unsuitable for exciting the laser transitions within the CO₂ laser because of the requirement for the average gas temperature to remain below 270°C to avoid filling of the lower laser levels and destroying the population inversion (De Maria 1973). The arc discharge also does not satisfy the requirement for the electron temperature to be around 1 eV in order to obtain a high efficiency in transferring energy from the electric discharge to the upper vibrational levels of the CO₂ and N₂ molecules (De Maria 1971, Bullis et al 1973).

The transition from the glow discharge to an arc discharge is characterised by the following observations:

(a) the cathode glow which uniformly covers the surface of the cathode changes to a number of intensely bright arc spots of high current density which usually produce flares of metal vapour and erosion of the cathode surface (Guile 1971). The spectrum of the light emitted from the cathode
region changes from an emission spectrum associated with the type of gas in the cathode region to a spectrum containing spectral lines associated with the metal ions displaced from the cathode surface (Ivenchenko 1969).

(b) the diameter of the positive column of a glow discharge is normally larger than the column of the arc discharge which at a constant power input results in an increase in the intensity of the light emitted and also the average gas temperature. At low pressures (around 40 mb) it can be difficult to distinguish between a glow and an arc column if the gas flow is sufficiently turbulent to uniformly distribute the discharge columns.

(c) the discharge voltage and current change from the high voltage, low current regime of the glow discharge to the lower voltage, higher current regime of the arc discharge. The transition region is often accompanied by rapid fluctuations between these two states until either the external circuit conditions or other parameters allow one state to become stable. Under these conditions filamentary arc streamers can be seen in the column of the glow discharge.

The factors influencing the current at which the glow to arc transition occurs can be broadly divided into two areas - electrode dominated processes and column dominated processes. A review of these factors is discussed below.
4.6.1 Electrode dominated processes

The electrode dominated process associated with the glow to arc transition may be divided into thermionic and non-thermionic mechanisms. The thermionic mechanism will be considered first.

The normal cathode current density is constant at a constant gas pressure and any increase in the discharge current causes an increase in the area of the negative glow on the cathode surface. When the cathode surface becomes completely covered by the negative glow further increase in discharge current leads to an increase in the cathode current density and the discharge enters the abnormal glow region. As the current density increases in the abnormal glow region the cathode fall thickness decreases. Since more charge carriers are crossing the region less distance is required to maintain the necessary ionisation rates to sustain the discharge. The increase in electric field across the fall region increases the energy transferred to the positive ions which bombard the cathode surface and the positive ions which now have greater energy raise the temperature of the cathode surface. Cathodes made of refractory materials (such as nickel, tungsten or carbon) can reach temperatures high enough for thermionic emission to occur. The electronic current developed by a thermionically emitting cathode at a specific temperature is given by Dushman's equation (Dushman 1923, Richardson 1921). The increase in current produced by the thermionic emission increases the number of positive ions hitting the cathode surface which heats the cathode further enabling a lower voltage to maintain a given discharge current than if emission were by positive ion bombardment alone. Under these conditions the falling voltage-current characteristic of the arc discharge is established (Cobine 1955).
The factors controlling the current at which the transition occurs when using thermionically emitting cathodes are mainly those affecting the heat transfer at the cathode surface (i.e., gas type, gas pressure, gas flow rate and electrode size, shape and material). Several theories have been developed for predicting the thermionic glow to arc transition (Von Engel and Steenbeck 1934) but the application of these theories to specific experimental equipment is of limited use because of the number of variables involved. A detailed review of literature on the thermionic mechanism for the glow to arc transition is given by Meek and Craggs (1953).

For non-refractory cathodes, the glow to arc transition is not directly dependent upon raising the cathode to high temperatures to liberate many electrons. The mechanism suggested describes the initial formation of a high current arc root which then enables the fully developed arc discharge to form. The non-thermionic glow to arc transition occurs on a very fast time scale (<10 ns Westberg (1958)) compared with the thermionic condition which is a cumulative process leading to arc formation. The work of Plesse (1935), Westberg (1958), Pfeil and Griffiths (1959), Hancox (1960), Maskrey and Dugdale (1962) and Holiday and Isaacs (1966) all suggest that the main mechanism for the glow to arc transition occurring with non-thermionic cathodes is dependent upon the presence of insulating particles on the cathode surface. The insulating particle becomes charged by positive ion bombardment to a potential high enough to cause breakdown, producing a burst of vapour. This condition only occurs for a range of particle sizes which depend on the cathode current density and cathode fall voltage. Once the vapour is produced, the increased conductivity of the region causes a local increase in current density which further increases the amount of vapour produced and the high current density
arc root site is established. The sites of arc roots coincide with sites of low conductivity inclusions—high conductivity inclusions have no effect. Insulating particles sprinkled on the surface of the cathode have the same effect as embedded inclusions (Pfiel and Griffiths 1959). Materials can be rendered less prone to arcing with heat treatment to remove surface contaminants and polishing of the metal surface (Maskrey and Dugdale 1962). A direct correlation was found to exist between the arc rate and the impurity content of the cathode (Holiday and Isaacs 1966, Fan 1939). The presence of low work function layers will permit the glow to arc transition to occur even at the low current densities associated with the normal glow discharge (Cobine 1955). An extensive review of the non-thermionic glow to arc transition is given by Lutz (1973).

4.62 Column dominated processes

The occurrence of the glow to arc transition (also referred to in the literature as plasma constriction, contraction and glow collapse) can occur even when the electrodes are carefully designed taking into account the observations discussed above. The glow to arc transition is also caused by an increase in gas pressure or discharge current and can be attributed to non-uniform heating of the discharge medium (Ecker et al 1964, Baranov and Ul'yanov 1969). The discharge becomes unstable and collapses into arc-like filaments or streamers and is accompanied by a substantial drop in the electron energy (below 1 eV) which results in the destruction of the population inversion and hence laser output (Wasserstrom et al 1978). The main mechanism appears to be as follows: a nonuniformity in the gas flow or discharge current density leads to uneven heating of the gas and hence a local decrease in the gas density. This raises the electron temperature, electron
density and hence the electrical conductivity. The increase in local current density increases the electrical heating which raises the temperature even further thus causing instability (Ecker et al 1964). Since the discharge instability can be initiated by an uneven temperature distribution, modification of the gas flow to develop more uniform Ohmic heating of the medium through the controlled use of uniform turbulence could be expected to offset the current at which the glow to arc transition occurred.

The causes of these thermal instabilities leading to the glow to arc transition were investigated by Nighan et al (1974), together with an analysis of the collision processes in the plasma and the growth time of the instabilities in the discharge column. It was found that if the growth time of the instability was less than the dwell time of the gas flowing through the discharge then the glow to arc transition occurred. Conversely if the growth time of the instability was greater than the dwell time of the gas then any streamer which formed in the positive column was convectively removed from the discharge before catastrophic collapse of the whole column occurred. The dwell time of the gas is dependent on the velocity of gas flowing through the discharge tube. Nighan and Weigand (1974) developed a theoretical treatment to predict the growth times of instabilities for a range of electrical input power densities. The model indicated that the growth time of an instability decreased with increasing power density, gas pressure and gas temperature. Experimental work carried out indicated that with a gas dwell time of 10 ms a power density of 0.5 mW/mm$^3$ was sustained before arcing, but that when the gas dwell time was reduced to 1 ms the input power density could be raised to 10 mW/mm$^3$. It was also observed that arcing always occurred at a distance downstream of the upstream electrode, regardless of polarity, corresponding to a gas
dwell time of 1 ms. The results indicate the importance of gas velocity in offsetting the glow to arc transition.

4.7 DISCHARGE STABILISATION

A glow discharge has a negative dynamic resistance at low currents (in the subnormal glow region) and cannot be operated directly from a constant voltage power supply. At higher currents the voltage current characteristic becomes flat (in the normal glow region) and eventually becomes positive (in the abnormal glow region). The latter regions would in theory enable operation with low or even zero stabilising impedance if it were not for the glow to arc transition which takes place as the discharge current is increased beyond a critical value forcing the discharge from the positive dynamic resistance region to the negative dynamic region of the arc discharge. For this reason a discharge is usually stabilised by resistance (for a d.c. supply) or impedance (for an a.c. supply) in series with the discharge and power supply.

The conditions for maintenance of a discharge are defined by the Kaufmann criterion (Kaufmann 1900) which may be stated mathematically as

$$\frac{dV}{dl} + R > 0$$

A d.c. discharge circuit and voltage current characteristic are shown in Fig 4.4. The discharge characteristic and the power supply load-line intersects at points A and B such that
\[ V_d = V_o - IR \]  \hspace{1cm} (4.2)

If the discharge operates at A and a disturbance momentarily causes the discharge to operate at point C then

\[ V_o - IR - V_d = \Delta V \]  \hspace{1cm} (4.3)

since \( \Delta V \) is now positive and the applied voltage \( V_o \) is greater than the sum of the discharge voltage and the voltage dropped across the resistance \( R \), the discharge current will tend to increase and the operating point will again become point A.

If the operating point is displaced to D, then the voltage \( \Delta V \) becomes negative and the discharge current is forced to reduce because of insufficient voltage available from the power supply and the system is restored to point A, which is known as the stable operating point. The operating point B may appear to be stable but if a slight increase in discharge current occurs, since \( \Delta V \) is positive, a further increase in current will occur because the supply voltage exceeds the sum of the \( V_d \) and IR, and the discharge is driven toward the stable operating point at higher current (A). A slight decrease in discharge current at B results in \( \Delta V \) being negative, causing a further decrease in discharge current and the discharge is extinguished. Thus point B is not a stable operating point.

The generalised discharge voltage characteristic is shown in Fig 4.5 with a number of power supply load lines plotted. When the applied voltage is \( V_1 \) the discharge characteristic is cut at points G, D, E, and F. By equation 4.3 only points D and F are stable. The point at which the discharge operates depends upon the method of initiating the
Fig 4.4 DC discharge circuit and associated voltage current characteristic

Fig 4.5 Generalised discharge voltage-current characteristic with two power supply load-lines
discharge. If the discharge is initiated by bringing the electrodes in contact with each other then the arc discharge will occur at point F. However if the discharge is initiated by slowly decreasing the resistance the glow discharge will probably be maintained at D. Increasing the supply voltage from \( V_1 \) to \( V_2 \) for a fixed resistance will result in two new points of stability A and C. Thus by varying the supply voltage with a sufficiently high value of stabilising resistance, the complete discharge voltage-current characteristic may be investigated. The lowest arc or glow current that can be obtained from a given applied voltage is the current for which the load line is a tangent to the discharge characteristic. A lower discharge current than this can be obtained only by increasing the supply voltage and the series resistance. Values of stabilising resistance ranging from 1 k ohm to 30 k ohm have been used to stabilise glow discharges in \( \text{CO}_2 \) lasers. As the value of stabilising resistance is increased the load line (Fig 4.5) is moved upwards enabling the glow discharge to be operated at lower values of discharge current. This is particularly important for \( \text{CO}_2 \) lasers where the turn down ratio of the laser output power is dependent on the range of stable glow discharge currents.

4.8 MULTIPLE DISCHARGES

Multiple discharges consist of a number of individual discharges which are operated in close proximity to one another so that they interact electro-magnetically. Multiple arc discharges have been reported in the literature as a technique of producing a high current, large volume of ionized gas for applications including metal melting and reduction of ores (Harry and Knight 1983, Harry 1983). Quasi-multiple discharges incorporating either multiple cathodes coupled to a single anode or multiple anodes coupled to a single
cathode have been reported for transverse CO₂ lasers (Eckbreth and Davies 1972, Artamonov et al 1977, Hill 1971). These configurations have been used with varying degrees of success. The multiple anode, single planar cathode configuration used by Hill (1971) yielded the most impressive results using aerodynamic flow conditioning techniques with a dc discharge to obtain a gas power loading of up 580 kW/kg/s. There have been few reports in the literature on the application of multiple discharge CO₂ lasers incorporating separately stabilised multiple anodes and multiple cathodes in either transverse or fast axial flow lasers (Saleh 1981, Harry and Saleh 1982).

The use of separately stabilised multiple cathodes reduces the discharge current associated with each cathode to below that which would occur with a single cathode system. A reduction in the individual cathode current should enable extended operation in the normal glow region and an increase in the current at which the glow to arc transition occurs. The use of a single electrode limits the utilisation of the laser cavity in the single electrode region (see Fig 3.6) and also the lower range of discharge currents to maintain uniformity of the discharge particularly with a single cathode. If the discharge current is reduced the area of the cathode glow is reduced and so the cathode glow decreases in area causing the discharge column to contract in the transition region between the fully developed column and the cathode. By using a number of separately stabilised cathodes the discharge is forced to locate on each of the cathodes and discharge uniformity should be maintained even at low total discharge currents.

The use of separately stabilised multiple anodes will tend to spread out the discharge in the multiple anode region and improve the
utilisation of the laser cavity. The use of flow conditioning techniques might then be applied to each anode which is then carrying a lower discharge current and may therefore have a greater response to the flow conditioning. This is explored further in chapter five where different multiple electrode configurations are investigated and in chapter six where the response of the multiple discharges to aerodynamic flow conditioning techniques is examined.
5.0 INTRODUCTION

The production of a uniform large volume glow discharge at gas pressures below 10 mb is relatively independent of the electrode configuration. At the pressures appropriate to high power CO$_2$ lasers (typically 20-60 mb) the volume and stability of the glow discharge becomes critically dependent on the electrode configuration. Results have been reported on various electrode configurations but only Saleh (1981) considered the operation of a number of discharges in a single tube with separately stabilised multiple anodes and cathodes. The maximum glow discharge current obtained by Saleh was 0.24 A which corresponded to a laser output power of 4 W. The very low laser output was probably due to the constricted nature of the glow discharge which resulted in thermal depopulation of the lower laser levels. The work of Saleh did, however, demonstrate something of the potential of using separately stabilised multiple electrodes.

This chapter describes the investigations and techniques used to operate a number of glow discharges together in a single discharge tube to produce a large volume coalesced glow discharge. The investigations include the determination of the glow discharge characteristics for different combinations of both multiple and single electrode configurations with different surface areas operating over a range of gas pressures. The effect of changing these parameters on the power limiting glow to arc transition is also investigated to try to increase the maximum glow discharge current in fast axial flow lasers. Increasing the maximum glow discharge current above those presently reported in commercial fast axial flow lasers (around 150
mA) would enable a correspondingly higher laser output per unit length of discharge.

5.1 THE MULTIPLE GLOW DISCHARGE TEST EQUIPMENT

To study the behaviour of multiple glow discharges operating at low pressures (20-60 mb) in a flowing gas, a gas system was designed which incorporated six anodes and six cathodes at each end of a glass discharge tube (Fig 5.1). The 3 mm diameter 2% thoriated tungsten electrodes were each resistively stabilised to ensure uniform distribution of the discharge current to each of the electrodes. A Pyrex glass tube 69 mm internal diameter and 500 mm long contained the glow discharge in the flowing gas. A standard laser gas mixture (82% He, 13.5% N\textsubscript{2}, 4.5% CO\textsubscript{2} by volume) was supplied from a gas cylinder and was pumped through the discharge tube to atmosphere by two rotary vane vacuum pumps connected in parallel to maintain a low pressure (typically 30 mb) in the equipment at gas flow rates of up to 100 m\textsuperscript{3}/h. The rotary vane vacuum pumps were later replaced with two Roots blowers used to recirculate the laser gas at flow rates of up to 400 m\textsuperscript{3}/h. The power supply (Fig 5.2) was designed to supply a variable direct voltage of up to 10 kV at a total current of up to 2 A. Each electrode was resistively stabilised using 10 kohm, 300 W wire wound resistors. The discharge voltage and current were measured for each electrode pair and the gas flow rate, pressure and temperature were recorded.

5.2 DETERMINATION OF A MULTIPLE GLOW DISCHARGE VOLTAGE CURRENT CHARACTERISTIC OVER A RANGE OF GAS PRESSURES.

A series of tests were carried out to determine the variation of
Fig 5.1 Multiple glow discharge equipment
Fig 5.2 High voltage dc power supply
discharge voltage with current of a multiple glow discharge. Six separately stabilised anodes and cathodes were used at an electrode separation of 500 mm in a gas flow of 100 m$^3$/h at an initial gas pressure of 24 mb.

The multiple discharge voltage current characteristic is shown in Fig 5.3 with the different discharge regions indicated. The term discharge current used in all the following tests refers to the total discharge current, rather than to the individual electrode current. The normal glow discharge region extended to stable discharge currents of up to 0.6 A, about four times the discharge current typical of fast axial flow CO$_2$ lasers. As the current was increased further the discharge voltage also increased, a characteristic of the abnormal glow discharge. At a discharge current of around 0.9 A the glow to arc transition occurred accompanied by the formation of arc spots on the cathode surface and fluctuation of the instruments recording the discharge voltage and current from the low current, high voltage condition of the glow discharge to the lower voltage, higher current condition of the arc discharge. The discharge was unstable over a range of discharge currents from 0.9 A to 1.1 A. At discharge currents above this range a stable arc discharge formed characterised by the falling voltage current characteristic and the presence of arc spots instead of a negative glow covering the cathodes. Although the discharge current of 0.9 A was higher than that reported elsewhere, the gas exit temperature was around 400 °C making the glow discharge unsuitable for laser excitation. The multiple electrodes did, however, enable stable operation of the glow discharge with the potential for using high gas flow rates to maintain the temperature below 270 °C. This is considered further in Chapters 6 and 7.
Fig 5.3 Variation of discharge voltage with current of multiple discharges

glow discharge

arc discharge
The gas pressure in the discharge tube was varied over the range 24-86 mb under conditions of constant gas flow rate. The maximum gas pressure (86 mb) was limited by the maximum output voltage of the power supply. The voltage current characteristics for both the glow and arc discharges are shown in Fig 5.4. The results show that an increase in the gas pressure raises the normal glow plateau voltage due to the increased loses by collisions between the charge carriers and neutral particles. As the pressure is increased the mean free path of all the particles is reduced because of the greater density of both neutral and charged particles within the smaller diameter positive column. The decrease in column diameter is due to the larger hydrostatic forces acting upon the fluid conductor. To maintain a given discharge current a higher electrical field is required to sustain the same rate of charge transfer through the conducting medium in which greater losses then occur due to the increased collision cross-section of the charge carriers and neutral particles. The average electric field strength in the positive column was found by subtracting the anode and cathode fall voltages from the total discharge voltage and then plotting this against gas pressure for several discharge currents. The results shown in Fig 5.5 indicate that the electric field strength is proportional to the gas pressure over the range investigated and is consistent with the mechanism suggested above.

The abnormal glow discharge occurs at a discharge current of 0.55 A at a pressure of 24 mb but at a gas pressure of 86 mb the normal glow region extended to a current of greater than 1 A. The rise in discharge voltage in the abnormal glow region is associated with the rise in cathode fall voltage which occurs when the cathodes become completely covered with the negative glow. As the current is
Fig 5.4 Variation of discharge voltage with current of multiple discharges over the pressure range 24-36 mb
Fig 5.5 Variation of discharge electric field strength with gas pressure
increased further the current density at the cathodes rises resulting in a rise in fall voltage because of the increased charge density associated with the larger number of electrons leaving the cathode region. The abnormal glow occurs at lower currents at lower pressures because of the larger area of negative glow covering the cathode surfaces. The area of the negative glow is inversely proportional to the square of the pressure resulting in larger changes in area for small changes in gas pressure. The cathode surfaces will therefore be covered with the negative glow at lower pressures resulting in the abnormal glow discharge at lower currents for cathodes of constant surface area.

The use of separately stabilised multiple electrodes has enabled operation of glow discharges at discharge currents of more than 1 A representing a substantial increase over single glow discharge currents typical of high power fast axial flow CO$_2$ lasers.

5.3 INVESTIGATIONS COMPARING THE ELECTRICAL CHARACTERISTICS OF A RANGE OF MULTIPLE GLOW DISCHARGE CONFIGURATIONS.

It has been shown in the previous section that the use of separately stabilised multiple electrodes can enable the total glow discharge current to be raised from around 0.15 A to currents of nearly 1 A. The following investigations were carried out to identify the effects of varying the number of electrode pairs, the importance of separately stabilising each of the electrodes, the relative effects of operating with either multiple anodes or multiple cathodes and the advantages of multiple electrodes over single large surface area electrodes.
5.3.1 The Effects of Increasing the Number of Electrode Pairs

A series of tests were carried out to determine the voltage current characteristics of glow discharges using from one electrode pair to six electrode pairs (Fig 5.6). As the number of electrode pairs was increased so the range over which the glow discharge was stable also increased. The abnormal glow region and the glow to arc transition occurred at progressively higher discharge currents as the number of electrode pairs was increased. The gas pressure of 24 mb and the gas flow rate of 100 m$^3$/h were held constant throughout the tests to assess the effects due only to electrode configuration.

The current density at each cathode may be defined as the current conducted by that cathode divided by the surface area of the negative glow on the cathode surface exposed to the discharge. The cathode current densities at which the discharge became abnormal and at which the glow to arc transition occurred for the range of electrode pairs investigated are shown in Table 5.1.

<table>
<thead>
<tr>
<th>No. of pairs of electrodes</th>
<th>Current density at start of abnormal glow, $J_a$ (A/m$^2$)</th>
<th>Current density at start of discharge instability $J_i$ (A/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>474</td>
<td>1315</td>
</tr>
<tr>
<td>2</td>
<td>578</td>
<td>1263</td>
</tr>
<tr>
<td>3</td>
<td>592</td>
<td>1280</td>
</tr>
<tr>
<td>6</td>
<td>561</td>
<td>1263</td>
</tr>
<tr>
<td>Mean value</td>
<td>551</td>
<td>1280</td>
</tr>
</tbody>
</table>

Table 5.1 Cathode current densities for different numbers of electrode pairs.
Fig 5.6 Variation of discharge voltage with current for different numbers of electrode pairs
The figures in Table 5.1 show that the value of cathode current density $J_a$ is similar for all the multiple electrode configurations and the figures indicate that increasing the number of electrode pairs should therefore enable higher normal glow discharge currents to be sustained for a given set of conditions. A mean value of $J_a = 551 \text{ A/m}^2$ can be used to select the size of electrodes for a glow discharge operating at a given discharge current at a gas pressure of 24 mb. The current density at the cathode is also proportional to $P^2$ so that the size of electrode operating at different gas pressures could be determined. If the surface area of a cathode is greater than the surface area of the negative glow, then the current at which glow to arc transition occurs becomes dominated by the column conditions rather than the cathode conditions. The results also indicate that the glow to arc transition occurs when the cathode current density $J_1$ exceeds a mean value of $1280 \text{ A/m}^2$ independently of the number of electrode pairs used. Both of these observations suggest that the surface area of the cathodes is of great significance with respect to the operation of a high current normal glow discharge and the suppression of the glow to arc transition region to higher discharge currents. The role of surface area in the context of separately stabilised multiple electrodes is considered further in Section 5.3.4.

As the number of electrode pairs was increased the discharge tube was filled more uniformly, the discharge improved, particularly in the electrode region. The photograph in Fig 5.7 illustrates the branching of the positive column into two transition regions near the cathodes with two electrode pairs connected.
5.3.2 Discharge Characteristics for Multiple Electrode Configurations With and Without Separate Stabilisation.

The voltage-current characteristics of a discharge with multiple electrodes were determined for both separately stabilised electrodes and electrodes connected together without separate stabilisation (Fig 5.8). The two electrode configurations, each with six electrode pairs, provided the same surface area to the discharge enabling the effectiveness of separate stabilisation of electrodes to be assessed.

The electrode configuration without separate stabilisation was unstable, particularly in the anode region where the discharge was only attached to one anode at a time, moving rapidly from one anode to another. All of the cathodes exhibited the characteristic negative glow but a few cathodes appeared to have a larger glow area than others suggesting unequal current sharing. This was not observed when separate stabilisation of the electrodes was used and may be due to an asymmetric gas flow influencing the distribution of the discharge in
Fig 5.8 Variation of discharge voltage with current for electrode configurations with and without separate stabilisation.
the cathode region. The voltage required to initiate the discharge without separate stabilisation of electrodes was more than double that required for the other configuration. The discharge exhibited a number of the characteristics of a single discharge including a smaller column diameter, a narrower range of normal glow current and the more abrupt change from the glow to arc discharge which was observed with the small surface area, single electrode pair in Fig 5.6. The glow to arc transition occurred suddenly without the more gradual signs of instability in the discharge voltage and current characteristic of multiple electrodes with separately stabilised electrodes. Once the arc discharge had developed only one anode and one cathode were involved in the conduction process.

The investigations showed the improvement obtained using separate stabilisation of each electrode on the characteristics and stability of the discharge over the same electrode system without separate stabilisation. The results here show that the practice commonly employed in transverse flow lasers (eg Hill 1971) of using multielement cathodes without separate stabilisation of each element is inferior to separately stabilised multiple cathodes.

In the following section the number of separately stabilised anodes and cathodes used is varied to investigate the relative importance of anode and cathode stabilisation.

5.3.3 The Electrical Characteristics of Multiple Discharges combining Multiple Electrodes with Single Electrodes.

The advantages of using both multiple anodes and cathodes has been demonstrated in the previous sections. The following series of tests
were carried out to determine the relative importance of using multiple anodes and multiple cathodes.

The single cathode and multiple anode configuration was tested first and resulted in an extremely unstable discharge. The voltage required to initiate the discharge was greater than that of any of the previous configurations tested and as the discharge current was increased the discharge changed from a subnormal glow (characterised by the negative slope on the voltage-current characteristic Fig 5.9) to the glow to arc transition. The positive column of the discharge decreased in diameter toward the cathode region and moved erratically from side to side in the discharge tube under the influence of the gas flow.

The single anode and multiple cathode configuration resulted in a stable discharge with a voltage-current characteristic which resembled a multiple anode and multiple cathode characteristic (both characteristics are shown in Fig 5.9). An abrupt change from the normal to abnormal glow discharge occurred at a discharge current of around 0.5 A at which point the discharge voltage increased rapidly with discharge current. The glow to arc transition occurred at a lower discharge current than in the multiple electrode configuration and a reduction in the positive column diameter was observed in a direction toward the anode region.

The results of these tests indicate that the use of separately stabilised multiple cathodes contributes more to the discharge stability and voltage-current characteristics than the use of separately stabilised multiple anodes. The final series of tests in the following section compare the operation of a glow discharge using a
Fig 5.9 Variation of discharge voltage with current for multiple anodes and a single cathode, multiple cathodes and a single anode and multiple anodes and cathodes electrode configurations.
single pair of electrodes with a discharge using separately stabilised multiple electrodes of the same combined surface area.

5.3.4 A Comparison between large surface area single electrodes and separately stabilised multiple electrodes.

A series of tests were carried out to investigate the effects of operating a discharge using a single pair of large surface area electrodes compared with three separately stabilised electrodes whose combined surface area equalled that of the single electrode pair. The test was designed to show whether the discharge characteristics are changed simply through variations in electrode surface area or whether separate stabilisation of multiple electrodes offers some other advantage not obtained through large surface area single electrodes alone.

Three electrode configurations were tested; a single anode and cathode each with a surface area of 73 mm$^2$, a single electrode pair of large surface area three times the surface area of the previous electrodes (ie 220 mm$^2$) and finally three separately stabilised electrode pairs with a combined surface area of 220 mm$^2$. The surface area of the electrodes was divided equally between the anodes and the cathodes. A gas flow rate of 200 m$^3$/h and gas pressure of 21 mb were maintained constant through the tests.

The discharge voltage-current characteristics corresponding to the three electrode configurations used are shown in Fig 5.10. The discharge obtained using the single electrode pair with a small surface area (73 mm$^2$) entered the abnormal glow region at a discharge current of only 0.035 A and the glow to arc transition at a current of
Fig 5.10 Variation of discharge voltage with current for multiple and single electrodes of the same total surface area.
0.1 A. This configuration exhibited the least stability of all the electrodes tested. The single electrode pair with a large surface area (220 mm$^2$) sustained a normal glow discharge of up to 0.1 A, three times that of the first arrangement, consistent with there being three times the surface area available for conduction at the cathode. The glow to arc transition occurred abruptly at 0.14 A, about 0.04 A higher than with the small surface area electrodes. The multiple electrode configuration with the same surface area (220 mm$^2$) as the large area electrodes exhibited the greatest stability of all the electrodes tested sustaining a glow discharge at currents of up to 0.3 A, twice that obtainable with the large single pair of electrodes.

The results of these tests demonstrate that separately stabilised multiple electrodes are able to operate in a stable mode at higher currents than the equivalent surface area single electrodes. Examination of the current densities at the start of the abnormal glow region ($J_a$) showed that these were similar for all three electrode configurations tested (Table 5.2).

<table>
<thead>
<tr>
<th>Electrode Arrangement</th>
<th>Area (mm$^2$)</th>
<th>$I_a$ (A)</th>
<th>$J_a$ (A/m$^2$)</th>
<th>$I_i$ (A)</th>
<th>$J_i$ (A/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small area single anode and cathode</td>
<td>73</td>
<td>0.03</td>
<td>411</td>
<td>0.1</td>
<td>1370</td>
</tr>
<tr>
<td>Large area single anode and cathode</td>
<td>220</td>
<td>0.1</td>
<td>455</td>
<td>0.15</td>
<td>685</td>
</tr>
<tr>
<td>Multiple small area anodes and cathodes</td>
<td>220</td>
<td>0.12</td>
<td>545</td>
<td>0.3</td>
<td>1370</td>
</tr>
</tbody>
</table>

Table 5.2 Cathode currents and current densities at the onset of the abnormal glow and glow to arc transition.
The current density at which the glow to arc transition occurred ($J_i$) however was quite different for the large surface area single electrode pair (685 A/m$^2$) compared with the other two electrode configurations (1370 A/m$^2$). Operation of the discharge with separately stabilised multiple electrodes reduces the current in the transition regions between the positive column and the fall regions by a factor equal to the number of electrode pairs used ($n$). Since the self-magnetic force $F$ associated with a conductor carrying a current $I$ is given by

$$F = \frac{\mu_0 I^2}{2\pi r}$$

where $\mu_0$ = absolute permeability of free space

$r$ = radius of conductor

the constricting force $F$ is proportional to the square of the current, the force is reduced by a factor $n^2$ when using multiple electrodes. This potentially large reduction in the magnitude of $F$ enables the negative glow to expand across the cathode surface utilising all the available conducting area, increasing the maximum glow discharge current and improves the spatial uniformity of the discharge in the cathode region.

The results show that the increase in maximum glow discharge current using multiple electrodes is attributable not simply to the increase in cathode surface area but also to the reduction in current density in the transition regions between the cathodes and the fully developed column which enables more of the cathode surface to be utilised at high discharge currents.
5.4 SUMMARY OF RESULTS

The voltage-current characteristics of multiple discharge systems operating at pressures in the range of 24-86 mb in a flowing gas have been investigated and the changes in behaviour of the discharge recorded as the configuration of separately stabilised electrodes was varied.

The use of multiple electrodes has enabled the maximum glow discharge current to be raised from 0.035 A to around 1 A representing a substantial increase over the maximum discharge current typical of high power fast axial flow CO₂ lasers.

A comparison of the discharge behaviour was made between a multiple electrode arrangement with and without separate stabilisation and the advantages of separate stabilisation of each electrode clearly demonstrated.

The electrical characteristics of multiple discharges combining multiple electrodes with a single electrode of the opposite polarity were determined. A wide variation in discharge stability was observed for the configurations tested and the results showed that the optimum arrangement was multiple anodes and multiple cathodes. Multiple cathodes were found to have a greater influence on the discharge behavior than multiple anodes.

A study was made of the relative effects of cathode surface area and current density with a single pair of electrodes and separately stabilised multiple electrodes of the same total surface area. The multiple electrodes enabled stable glow discharge currents of more...
than twice those achieved with the single large surface area cathode to be sustained. A cathode current density of 1370 A/m$^2$ was obtained with the multiple electrodes before the glow to arc transition occurred compared with only 685 A/m$^2$ with the single cathode. It is suggested that the reason for this difference in cathode current density was because of the reduction in discharge current (and hence the magnetic constrictive force) associated with the discharge in the transition regions between the cathode negative glow and the fully developed positive column reducing the tendency of the abnormal glow to degenerate to an arc discharge.

The work described in this chapter has been published or submitted for publication as follows:


6.0 INTRODUCTION

The behaviour of a multiple glow discharge in a low speed gas flow was investigated in the previous chapter. Electrical input powers of up to 2 kW were achieved in a large diameter discharge tube through the use of a unique configuration of large area separately stabilised multiple electrodes. The electrical power input to the flowing gas in a high power CO$_2$ laser is limited by the maximum temperature of the lasing medium (270°C). To increase the electrical power input to around 20 kW, high velocity recirculating gas flows are needed to convectively remove the heat from the discharge. The behaviour of a glow discharge under these conditions changes from the low power, low speed gas flow conditions investigated in Chapter 5 tending to constrict as the electrical power input, gas flow rate and pressure are increased developing into an arc discharge which is unsuitable for laser excitation. This chapter describes techniques investigated to overcome this constriction of the discharge. The investigations are carried out in a high power CO$_2$ laser incorporating a high velocity recirculating gas flow through a large diameter laser cavity applying the multiple glow discharge principles developed in the previous chapter.
6.1 GAS RECIRCULATING LASER

6.1.1 Gas Flow System

The multiple discharges investigated in Chapter 5 enable operation of a large diameter discharge tube at correspondingly lower differential pressures making possible the use of a vane axial fan to recirculate the gas. The vane axial fan has been used extensively in transverse flow lasers where the large cross-sectional area cavity presents only a low pressure drop (typically around 0.2 mb) enabling large gas flow rates to be recirculated through the laser cavity by a small, economical, oil-free fan. The vane axial fan provides major advantages over the large positive displacement Roots blowers which are expensive, require high power drive motors and can contaminate the laser with oil from the gear boxes.

The photograph in Fig 6.1 shows the gas recirculating system. The system was designed to circulate gas at pressures of 40 mb at flow rates of up to 2 m$^3$/s to enable up to 20 kW of heat to be removed from the glow discharge. The system comprised a high speed vane axial fan, associated pipework, a discharge tube and a heat exchanger.

The total pressure drop around the gas recirculating system is the sum of the pressure drops across each element and is limited by the maximum differential pressure of the fan. The pressure drops around the system were calculated and the components selected to maintain the total pressure drop of the recirculating loop below the maximum pressure head available from the fan.

The performance of the single stage high frequency vane axial fan is summarised below in Table 6.1.
Fig 6.1 Gas recirculating system with high speed vane axial fan
Table 6.1 Summary of Performance of Aerology Model 1151 single stage Vane Axial Fan.

The single stage fan was later modified to a two stage fan to increase the differential pressure to 2.2 mbar. The addition of the second impellor and housing produced two resonances in the operating range. The fan was subjected to swept frequency vibration tests and the resonances eliminated by replacing the fabricated impellor with a cast impellor. The unit was then dynamically balanced to 1.5 gm-mm, (within category Q1 fine balancing, Code of Practice VDI 2056).

The heat exchanger was incorporated in the gas system to remove the heat generated by the electric discharge. The heat exchanger was constructed from stainless steel and had a thermal rating of 33 kW at a gas flow rate of 0.03 kg/s with a pressure drop of less than 0.2 mb in the gas flow path.

The pressure drops of components in the gas recirculating system were calculated using a program written for the Hewlett Packard HP41C Computer (Hewlett Packard 1980) and the schematic diagram in Fig 6.2 shows the completed gas flow system through the laser head with the critical dimensions of components with their associated pressure drops.
Fig 6.2 Geometry of the gas path through the laser cavity
6.1.2 Vacuum System

The vacuum system was constructed according to the following design requirements:

(1) the maintenance of laser gas at pressures below 80 mb with a leak rate of $< 10^{-6}$ mb.l/s.
(2) the use of clean and non-corrosive materials to sustain a medium vacuum ($<0.5$ mb) for up to 1 week.
(3) demountable components to enable rapid modifications to the gas flow paths.
(4) the use of diagnostic ports to connect instruments to measure operational parameters.

A summary of the elements and techniques used in the construction of the vacuum system is given in Table 6.2.

6.1.3 Electrical Power Supply

The maximum laser supply voltage was limited to 25 kV since direct voltages above this level can produce hazardous soft X-rays and the engineering of the insulation becomes increasingly more complex. The discharge was resistively stabilised at the six anodes and six cathodes with 10 kohm wirewound resistors. The ratio of the open circuit to discharge voltage was in excess of 2:1 to satisfy the empirically derived stability criterion (Section 4.7).

The details of the high voltage transformer are summarised in Table 6.3.
<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipework</td>
<td>Stainless steel schedule 10 pipe, Ø304</td>
<td>Type 316 stainless</td>
</tr>
<tr>
<td>Flanges</td>
<td>Machined from plasma cut rings surface finish &lt;50 μ flange design with twelve bolts, 25 mm thick TIG welded to pipe, external fillet, internal seal weld</td>
<td>Type 316 stainless BS4767, Table E</td>
</tr>
<tr>
<td>Seals</td>
<td>O-rings mounted in Klien fitting type carriers, Viton O-rings</td>
<td>Fluorocarbon</td>
</tr>
<tr>
<td>Diagnostic Ports</td>
<td>Klien fittings type 10 KF and 40 KF</td>
<td>Leak rate &lt; 10⁻⁹ mb.l/s</td>
</tr>
<tr>
<td>Expansion Bellows</td>
<td>Stainless steel, double skinned bellows, 45 corrugations per meter, flanged at each end, 380 mm long ± 30 mm expansion</td>
<td>BS4767, Table E</td>
</tr>
<tr>
<td>Bellows for optics</td>
<td>Stainless steel bellows, 150 mm long by 0100 mm</td>
<td></td>
</tr>
<tr>
<td>Glass discharge</td>
<td>Pyrex glass heavy wall tube 150 Ø/dia, 7 mm wall, 1 m long, ± 0.02 mm on diameter</td>
<td></td>
</tr>
<tr>
<td>Vacuum pump</td>
<td>Edwards Speedivac ISC450B rotary vane vacuum pump. Connected via foreline trap and gate valve</td>
<td>33 m³/h pump rate at 1 atm</td>
</tr>
<tr>
<td>Leak detector</td>
<td>Helium mass spectrometer type leak detector with built in rotary and diffusion pumps and an automatically controlled regulator valve. Liquid nitrogen cold trap</td>
<td>Sensitivity &gt; 10⁻¹⁰ mb.l/s</td>
</tr>
</tbody>
</table>

Table 6.2 Summary of Vacuum System components.
The maximum secondary voltage was obtained by connecting three secondary windings in series to form each arm of a delta configuration. The primary was supplied by a variable output voltage regulating transformer.

The direct current was supplied by two three phase full wave rectifying bridges. The bridges were designed to supply a direct current of 2.5 A with a peak inverse voltage rating of 45 kV. Each bridge was supplied by a separate three phase winding to obtain a total direct current rating of 5 A.

6.1.4 Optical Resonator

The optical resonator was designed to satisfy the following criteria:
(1) to maximise the utilisation of the large diameter discharge cavity
(2) to resonate with a stable multimode output beam
(3) to have low intracavity losses
(4) tolerance to small angular misalignments of the mirrors
(5) to operate with a high electrical to optical efficiency.

A stable long radius of curvature plano-concave resonator satisfies the above criteria. An unstable resonator configuration could have been used to extract power from the cavity but the marginal advantages over the stable resonator were thought to be insufficient to justify the greater complexity of the design of the unstable resonator.

The specification of the optics used in the resonator is given in Table 6.4.

<table>
<thead>
<tr>
<th>Rear mirror:</th>
<th>gold on nickle on copper substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>120 mm dia x 20 mm thick</td>
</tr>
<tr>
<td></td>
<td>20 m radius of curvature</td>
</tr>
<tr>
<td></td>
<td>water cooled</td>
</tr>
<tr>
<td></td>
<td>λ/20 flatness at 10.6 μm over 80% of area</td>
</tr>
<tr>
<td></td>
<td>60/40 scratch-dig cosmetic finish</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Front window:</th>
<th>zinc selenide substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AR/60% coating at 10.6 μm</td>
</tr>
<tr>
<td></td>
<td>plano-plano</td>
</tr>
<tr>
<td></td>
<td>120 mm dia x 10 mm thick</td>
</tr>
</tbody>
</table>

Table 6.4 Specification of the resonator optics.

The two mirrors were each mounted in aluminium holders using
0-ring vacuum seals and each mirror was water-cooled. The holders were held in three-point adjustable mirror mounts which were secured to a 200 mm square section steel beam by 25 mm thick steel plates bolted to the beam. The steel beam provided the necessary rigidity of the resonator. The beam was mounted on two 70 kg concrete pedestals which were positioned on top of anti-vibrational material. The large diameter mirrors were designed to withstand forces of 1100 N due to atmospheric pressure acting over the large cross-sectional area of the mirrors. The resulting angular stability was $> 0.1 \mu$rads. The optical resonator was aligned using a 1 mW helium-neon laser and beam expander. The beam expander was designed to fit directly on to the sighting laser and produce a well defined, circular beam over several meters. The beam expander consisted of a machined aluminium holder, a microscope objective ($f=10 \text{ mm}$), a 25 micron spatial filter and objective lens ($f=100 \text{ mm}$) and had a magnification factor of 10 times producing a parallel beam of 12 mm diameter. The collimated light source was mounted in an adjustable cradle which was fixed to a rigid structure bolted to the floor approximately 3 m from the output window of the CO$_2$ laser.

The alignment procedure was as follows. When imaginary lines drawn normal to the centre of each mirror coincide, the optical resonator is said to be aligned. The optimum alignment for laser operation occurs when the discharge axis coincides with the optical axis. The following procedure was used:

1. The He-Ne laser was set on the optical axis of the main laser using targets mounted in each of the mirror holders and adjusted until the beam passed through the centre of both the targets simultaneously.
(2) The rear mirror was then installed in the laser and adjusted until the reflected beam coincided with the centre of the aperture of the He-Ne laser.

(3) The front window was then installed in the laser and adjusted until the reflected beam from the front surface of the zinc selenide coincided with the aperture of the He-Ne laser.

6.1.5 Instrumentation of Laser

The gas flow rate recirculating around the laser was measured with a Pitot-static tube and an inclined tube differential manometer with a pressure range of 0-1 mb. The manometer was later replaced with an electronic capacitive differential manometer to overcome problems associated with evaporation of the paraffin manometer fluid under vacuum conditions. Traversal of the Pitot tube across the diameter of the 305 mm ducting enabled assessments to be made of the velocity profile of the flowing gas.

The average gas exit temperature from the discharge tube was measured using a fast response unsheathed chromel-alumel thermocouple supported on an earthed wire to reduce the possibility of unwanted spurious discharges to the thermocouple and indicator unit.

The average static pressure of the gas in the discharge cavity was measured by a number of capacitive manometers at positions both upstream and downstream of the discharge.

The discharge direct current was measured using direct current current transformers (DCCT's) as no part of the discharge circuit was earthed. Two transformers were used, one for each bridge rectifier
circuit, both excited by a single a.c. power supply.

The laser power was measured using an Ophir water-cooled, thermoelectric 1 kW laser power monitor. The monitor head contained a 32 mm diameter distributed thermocouple and was coated and ribbed to achieve high absorption of incident radiation at wavelengths around 10.6 microns. The thermal time constants associated with the disc, the support structure and water cooling were electronically compensated in the analogue display unit and the maximum response time to a step input of power from zero to 50% full scale deflection was 700 ms. The response of the instrument was fully investigated using a Coherent Everlase 525 500 W slow flow laser over a range of powers. An attenuating chopper was designed to increase the power range of the instrument from 1 kW to 6 kW whilst maintaining the 700 ms response time. A sodium chloride focusing lens with a 300 mm focal length to reduce the beam diameter of the laser from 93 mm to 15 mm to ensure that all the beam was detected.

6.1.6 Fibre Optic Remote Voltage Sensing Unit

The high voltage multiple glow discharge was stabilised on both sides with resistors. The discharge voltage was approximately 10 kV, the open circuit voltage of the power supply 25 kV and the cathode potential with respect to earth was up to 5 kV. No measuring equipment that was earthed could therefore be connected to this system. A means of providing an electrically isolated signal representing the direct voltage of the electric discharge was required. Several techniques were considered. Isolation transformers with d.c.-a.c. converters were available but did not provide the high level of electrical isolation required in the laser. Although a wide
variety of opto-isolators are available they are not suitable for use at these high direct voltages. The high direct voltage is exacerbated by the effect of switching transients which can result in instantaneous values of voltage as high as 100 kV. A transparent barrier eg a sheet of perspex could be used between the opto-isolator to increase the electrical isolation, although for complete protection of personnel and the computer data logger an air gap of at least 30 mm is required for the worst case conditions. Over such long path lengths a fibre optic cable between a separate transmitter and receiver is the most attractive choice.

The receiver was required to have an input impedance of $10^7$ Ohms to be compatible with the high voltage 1000:1 attenuating probes available and to transmit signals from 1 V to 25 V (equivalent to a discharge voltage of 1 kV to 25 kV) over a distance of at least 10 m. A frequency response of approximately 100 Hz was considered to be adequate for monitoring the d.c. discharge voltage which fluctuated only over a small range. The transmitter had to be powered by a battery pack to eliminate unwanted earth paths.

Two fibre optic remote voltage sensing units had been designed and built for operation with the equipment described in Chapter 5. The unit described here was designed by the author to have better linearity and frequency response and was then constructed and evaluated as part of a final year project initiated and supervised by the author (Dawson 1985). A block diagram of the transmitter and receiver is shown in Fig 6.3. The circuit diagram of the transmitter is shown in Fig 6.4. The transmitter uses a voltage to frequency converter with a frequency range of 10 Hz - 100 kHz. To obtain adequate response to fluctuations at low discharge voltages the lowest
Fig 6.3 Block diagram of the fibre optic remote voltage sensing system
Fig 6.4 Circuit diagram of fibre optic transmitter
frequency used was 1 kHz. The input voltage is amplified with a switched gain with a range of 1 to 1000 using an instrumentation amplifier and pulse width modulated by a voltage to frequency converter. The signal is then used to switch a transistor which drives an optical emitter connected in a sweet spot housing to the polymer fibre optic cable. The battery supply voltage is regulated with a Zener diode and a Schmitt trigger. An LED is used to indicate low battery voltage. A reference signal derived from a precision 8.2 V Zener diode provides a calibrated reference for the system and an LED indicates when the input voltage exceeds the maximum voltage for the gain selected.

The circuit diagram of the receiver is shown in Fig 6.5. The receiver is powered by an earthed 12-0-12 volt supply and the optical signal detected via a Schmitt receiver. The variable frequency signal is then demodulated by a frequency to voltage converter which provides a voltage level of 2.5 V for a discharge voltage of 25 kV. The linearity of the system was better than 0.2% of full scale input voltage. Printed circuit boards were produced for both the transmitter and the receiver. The frequency response of the unit was investigated by applying a sawtooth waveform to the transmitter input. The sawtooth became triangular in shape at frequencies above 150 Hz. An improvement in output signal was achieved by using a low pass filter circuit at the output terminals of the receiver with a cut off frequency of 250 Hz. The resulting signal was a completely isolated signal which was safe to connect to computer data logging equipment.

6.1.7 Development of a Computer Data Acquisition System

A data acquisition system was required to record up to six
Fig 6.5 Circuit diagram of fibre optic receiver
experimental parameters all of which were varying simultaneously with
time. The duration of each investigative test ranged from a few
seconds to several minutes. Manual methods of recording the data
under these conditions were not practical. A computerised data
logging system was developed to both record and analyse the
experimental data and to provide a practical engineering solution to
the problem of instrumentating the experimental laser system. The
following parameters were recorded from the laser:

- discharge voltage
- discharge current
- laser output power
- cavity gas pressure
- cavity gas exit temperature

From the above the following parameters were derived which are
of interest in assessing the operational performance of the laser:

- discharge power
- volume flow rate of gas through cavity
- electrical to optical efficiency
- electrical power loading of gas
- gas velocity in cavity
- \( E/N \), electric field strength to neutral particle
density
- \( E/p \), electric field strength to cavity gas pressure

An Intercole Systems Spectra-ms intelligent data logger was used
which had a capacity for recording up to 32 analogue signals at a
scanning rate of up to 20 \( \mu s \) per channel. The unit had facilities for
varying the sequence and rate of channel scanning, the integration period, the type of thermocouple linearisation, the type of user defined signal conditioning, full scale values, autocalibration rates and time and date stamping of individual data points. The flexibility and operation of the data logger was greatly enhanced by the use of an additional 'host' microcomputer communicating via the RS423 serial data port. A BBC model B microcomputer with twin 100 k disc drives, an Epson FX80 dot matrix printer and colour monitor completed the computer data logging hardware.

Extensive programing of the host computer was required to fully interface the data logging system with the laser system. Eight BASIC programs were written for the BBC microcomputer, each one loaded automatically for the options selected on the menu-driven programs. A summary of the program names and a brief description of their function is given in Table 6.5 and a full listing of the programs is given in Appendix 2. A 6502 second processor with an additional 64 kbit of random access memory was eventually required to accomodate the programs and operate the system at the required logging speeds. The second processor was used to maintain the screen disc and keyboard functions whilst the first processor communicated with the data logger and calculated the derived data values.

The menu-driven programs enabled initial definition of the channels and the facilities for each channel to be selected and stored in a group table which could be stored on the disc. The use of groups containing a number of channels made it possible to allocate different full scale values, integration codes etc to be assigned to different groups of channels. Data could then be logged to screen as a graph or table, to the screen with simultaneous logging to disc or just to a
<table>
<thead>
<tr>
<th>Program Name</th>
<th>Abbreviated Name</th>
<th>Program Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>OVERLOGGER</td>
<td>OVRLG</td>
<td>Sets up the group table containing individual channel facilities, editing of channels, titles, units, full scale values, produces main menu, sets real time.</td>
</tr>
<tr>
<td>SET UP LOGGER</td>
<td>SULGR</td>
<td>Sets scale factors, checks healthy condition of logger, notifies of set-up scan failure, permits manual calibration of system.</td>
</tr>
<tr>
<td>DISC INPUT</td>
<td>DSCIP</td>
<td>Creates user defined data files, directs raw and derived data files to preselected directories, opens and closes files as required.</td>
</tr>
<tr>
<td>GRAPH</td>
<td>GRPH</td>
<td>Produces a graph on the screen during logging of any selected parameter and provides option of saving a graph to the printer.</td>
</tr>
<tr>
<td>HEADER TABLE</td>
<td>TABL</td>
<td>Produces a tabularised summary of the current channel allocation, full scale values and engineering units.</td>
</tr>
<tr>
<td>LOGGER INPUT</td>
<td>LGRIP</td>
<td>Maintains communication between the BBC and logger during an experimental run, maintains the real time clock, selects interval between samples.</td>
</tr>
<tr>
<td>DERIVED TABULAR</td>
<td>TABULAR</td>
<td>Sets range of acceptable data, ignores out of range data, produces header table of derived results summarising experimental conditions with comments, time and date, calculates the derived parameters by user-defined equations, produces a menu of data file options to be examined and a choice of either tabular or graphical format.</td>
</tr>
<tr>
<td>DERIVED GRAPH</td>
<td>GRAPH</td>
<td>Produces a menu of the parameters available for plotting on any selected axis, options for saving the current screen to the printer, rescaling of axis, number of significant figures and decimal places, the option of examining new data from other files or returning to the main TABULAR menu.</td>
</tr>
</tbody>
</table>

Table 6.5 Summary of BASIC programs for the data acquisition system
user defined file on disc. The derived data was then calculated and a facility for examining the data in either tabular or graphical form provided. The graph option permitted any two parameters to be plotted against any other parameter. A header program enabled initial experimental conditions, comments, times and dates to be recorded with the experimental data. An example of the tabular data output from the computer for a typical test is shown in Table 6.6.

6.2 AERODYNAMIC MIXING TECHNIQUES

Gas flow rates of up to 1.9 m\(^3\)/s at gas pressures of up to 50 mb were achieved with the new recirculating system. Although multiple glow discharges of up to 2 A total discharge current were sustained in the high velocity gas flow the discharges were constricted filling around only 30% of the volume of the laser cavity. A series of tests were carried out to develop techniques for producing a uniform glow discharge which completely filled the discharge tube at electrical power inputs of around 20 kW. A range of aerodynamic flow conditioning elements to distribute the discharge were investigated and a summary of the results is given in Table 6.7.

The pressure drop across a flow conditioning element can be estimated by considering the momentum balance across the element.

If \( U_1 = U_2 \)

then \( P_1 A_1 + \rho_1 U_1^2 A_1 = F = P_2 A_2 + \rho_2 U_2^2 A_2 \)

therefore \( P_2 - P_1 = F/A_1 \)

\( \Delta P = \frac{1}{2} \rho U_1^2 A_e / A \)  \hspace{1cm} (6.1)
**Table 6.6 Output from the data acquisition system**

<table>
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<tr>
<th>DISCHARGE VOLUME</th>
<th>ELECTRICAL POWER</th>
<th>LASER POWER</th>
<th>GAS PRESSURE</th>
<th>VOLUME FLOW RATE</th>
<th>EFFICIENCY</th>
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<table>
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<tr>
<th>LASER POWER (W)</th>
<th>VOLUME FLOW RATE (CUBIC m/s)</th>
<th>EXIT TEMP (degC)</th>
<th>POWER LOADING (kW/kg/s)</th>
<th>VELOCITY (m/s)</th>
<th>E/N</th>
<th>E/P</th>
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<td>(a)</td>
<td>Vortex generator upstream of anode rods.</td>
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<tr>
<td>(b)</td>
<td>Plasma sprayed copper vaned anodes.</td>
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<td>(c)</td>
<td>Large vortex generator upstream of converging nozzle.</td>
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<tr>
<td>(d)</td>
<td>Annular rings upstream of anode rods.</td>
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<td></td>
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</tr>
<tr>
<td>(e)</td>
<td>Pyrophyllite cone attached to anode rods.</td>
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</tr>
<tr>
<td>(f)</td>
<td>Anode rods and wires mounted around cone.</td>
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<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Table 6.7 Aerodynamic flow conditioning elements
where 1 = upstream condition  \( F \) = force on element
2 = downstream condition  \( A_e \) = area of element
\( \rho \) = gas density  \( p \) = static gas pressure
\( P \) = static gas pressure  \( A \) = area of channel
\( U \) = gas velocity  \( \Delta P = P_2 - P_1 \) = pressure drop
across element

The following conclusions may be drawn from Equation 6.1:

(1) the higher the static gas pressure the higher the pressure drop for the same flow velocity since the gas density is directly proportional to gas pressure

(2) the pressure drop is proportional to the square of the gas velocity, hence a small increase in gas velocity results in a relatively large rise in pressure drop

(3) the pressure drop is proportional to the blockage factor (ie the ratio of the clear area through the element to the closed area).

The techniques applied must satisfy the following criteria:

(1) sufficient turbulence must be created to overcome the magnetic constrictive forces within the discharge
(2) low pressure drop across the flow conditioning element
(3) a clear optical path must be maintained through the laser.

To produce large amounts of turbulence work must be done on the flowing gas. This work has to change the flow direction and velocity and to develop the required turbulent flow conditions. The energy is
available only from the flowing gas. If a part of this energy is used to modify the flow in some way then the static pressure of the flowing gas will be reduced, resulting in a pressure drop across the flow conditioning element.

Vortex generators (Table 6.7(a)) were designed to add a swirl component to the flowing gas and to produce turbulence by ensuring flow separation on the downstream edge of the inclined blades. The distance of the vortex generator from the anodes had no effect on the discharge. The number of blades and the angle of inclination to the flow was varied over a wide range with little effect on the discharge. The intensity of the turbulence generated by this method was insufficient to disperse the discharge column downstream of the anodes. A larger vortex generator Table 6.7(c) was mounted in the 300 mm dia pipework just upstream of the converging nozzle to increase the intensity of the turbulence within the working section of the cavity. The effects were similar to the smaller vortex generator.

Aerodynamically shaped anodes (Table 6.7(b)) were tested to influence the gas flow near the anode root by causing flow separation in this region. The six electrodes were made from a copper plate, insulated over all surfaces except the downstream edge by a plasma sprayed alumina coating. The effects of the turbulence lasted approximately 20 mm and over this region caused an increase in the column diameter of around 50%. Intermittent discharges between adjacent anodes occurred at discharge currents in excess of 0.2 A.

A set of concentric annular rings (Fig 6.7(d)) was placed upstream of the rod anodes to produce an axially symmetric turbulent flow field around the anodes and in the discharge column region. The
diameter of the positive column was increased by about 25%. Constriction of the discharge increased rapidly above currents of 1 A and pressures of 20 mb. The rings were placed both upstream and downstream of the anodes but the effect on the column was most pronounced when the rings were placed immediately upstream of the rod anodes. This confirmed results reported in the literature indicating that creating turbulence in the anode region is important as well as creating a turbulent flow field in the discharge column region (Davies 1980).

To increase the turbulence in the anode region a heat resistant, pyrophyllite insulating cone (Table 6.7(e)) was positioned so that the anode rods protruded through the cone to maximise the interaction of the turbulent gas flow with the anode region. The rods were placed at a number of positions both inside and outside the cone. Severe inter-electrode breakdown limited the effectiveness of the turbulence generated by the cone.

Small angled extensions were positioned on the end of the rods (Table 6.7(f)) to move the anode root region to the extreme edge of the cone where the flow separation occurred. The discharge became diffuse downstream but then constricted indicating that if the discharge is maintained in a region of turbulence (the downstream edge of the cone) the aerodynamic forces successfully distribute the discharge uniformly. The turbulence generated by the cone did not extend far enough down the discharge tube to maintain the diffuse discharge. The separately stabilised angled extensions produced a very diffuse spray rather than the discrete columns observed with the rod anodes, but the effect lasted only 60 mm downstream.
A new anode head (Table 6.7(f)) was tested with 18 rod anodes, each separately stabilised to try to increase the volume of the discharge at the entrance to the laser cavity. The volume of the plasma immediately downstream of the anodes was larger than with the 12 anodes but contracted to about 50 mm diameter approximately 100 mm along the discharge tube. The length of individual columns associated with each anode could be increased by raising the value of the upstream (anode) stabilising impedance. A maximum impedance of 50 k ohm per anode produced well defined, uncoalesced columns which extended to the cathodes.

The previous tests illustrate that the techniques used to disperse the positive column were limited in their effect. Although up to 18 individual columns have been produced within the discharge tube, the techniques did not enable these columns to be dispersed and develop a large volume uniform coalesced discharge. The individual columns were estimated to fill approximately 35% of the cavity volume, therefore utilising only a low percentage of the gas flow. The temperature of these individual columns was measured with an insulated thermocouple and was found to be in excess of 400 °C. No laser output was observed during these tests. The results of the tests indicate that insufficient turbulence was generated by the flow conditioning elements used. The limitation on the head of pressure available from the vane axial fan (around 2 mb) prevented the application of any other flow conditioning methods being investigated.
6.3 MAGNETIC ROTATION OF THE GLOW DISCHARGE

6.3.1 Fast Axial Flow Laser

An alternative approach to generating turbulence within the discharge region is to use an external magnetic field which interacts with the electric discharge to cause rotation of the discharge within the laser cavity. Buczek (1970) used a magnetic field to move the glow discharge on the optical axes of the laser overcoming the force of the flowing gas, arc discharges have been rotated at high rotational frequencies in transverse magnetic fields (Harry 1968), and glow discharges have been rotated between coaxial electrode arrangements (Seguin et al 1981, Capjack et al 1981). The interaction of a rotating discharge in an axial gas flow would tend to cause a highly sheared flow developing a uniform discharge in a high speed gas flow. This arrangement would not require a large static head of pressure from the gas recirculating system since the turbulence could be generated by the interaction of the glow discharge with the magnetic field.

A series of tests were carried out to investigate the effects of applying a magnetic field coaxial with the direction of gas flow through the laser cavity in the vicinity of the anodes. Fig 6.6 illustrates the lines of flux of the axial magnetic field and the direction of discharge current at the anodes.

The resolved components of the discharge current and magnetic flux density are shown in Fig 6.7. The radial component of discharge current $I_r$ will interact with the axial component of the magnetic field $B_z$ causing rotation of the discharge in the anode head region. Further downstream little or no rotational force will be applied
Fig 6.6 Mechanical arrangement of the laser showing the position of the magnetic field coils, lines of flux and electric discharge

Fig 6.7 Schematic diagram showing the components of magnetic flux density and discharge current
because of the diminishing magnitude of the magnetic field and the smaller radial component of discharge current. It was anticipated that sufficient mixing of the plasma in the anode region would interact with the flowing gas producing a uniform discharge extending downstream to the cathodes.

The field coils consisted of 272 turns of 6.4 mm by 2.6 mm enamelled copper strip placed either side of the anode head. A maximum axial magnetic flux density of 0.015 T was developed at the anodes at a field current of 300 A. The field was measured with a Hall probe mounted in one of the anode assemblies.

The effect of the magnetic field on the discharge using rod anodes was merely to distort the positive columns such that they were displaced in the same clockwise direction, but no continuous rotation occurred. The discharges were prevented from rotating by the individual anode rods. The anode rods were replaced with fixed, separately stabilised copper rings which provided a continuous conducting surface inside the anode head. The discharge column then rotated in the axial gas flow but remained constricted along its entire length. Photographs were taken along the optical axis of the laser with the mirrors removed at a number of values of magnetic flux density (Fig 6.B). The most diffuse discharge was obtained at the highest magnetic field of 0.015 T. The rotational frequency of the discharge was estimated using a camera operating with a known shutter speed and was found to be around 30-40 Hz. The rotational frequency of the discharge was increased by around 10 Hz by recessing the anode rings into the anode head to increase the radial component of discharge current.
The tests indicate that over the range of discharge currents (1-2 A) and magnetic fields (0.002-0.015 T) rotational frequencies of up to 40-50 Hz can be obtained and that some improvement in discharge uniformity can be achieved immediately downstream of the anodes. The tests indicate that significantly higher rotational frequencies are required to completely break up the discharge and produce a uniform glow extending to the cathodes.

Further investigations are described in the next section to determine the suitability of this technique for producing a high power uniform glow discharge for laser excitation.

6.3.2 Coaxial Electrode Equipment

One of the principle limitations to rotating the glow discharge in the existing laser cavity was the small component of radial discharge current (<100 mA) and the low magnetic flux density (0.015 T) achievable with the 134 mm diameter discharge tube. It has been
proposed that the \( J \times B \) effect could be used to rotate glow discharges at high rotational velocities to produce glow discharge currents of up to 10 A (Seguin et al 1981, Capjack et al 1981). A series of tests were carried out to determine the range of conditions and suitability of magnetic rotation of the discharge for laser excitation.

The rotating discharge equipment is shown in Fig 6.9 and the circuit diagram in Fig 6.10. An anode 15 mm diameter was positioned coaxially within a 90 mm diameter tubular copper cathode. The electrode assembly was mounted in the bore of the field coil. The shape factor of the field coil was selected to obtain a high uniform magnetic flux density in the coaxial discharge region (Bruce-Montgomery 1961). The field coil was wound with 550 turns of 6.4 x 2.4 mm\(^2\) enamelled copper strip and the shape factor of \( G = 0.165 \) compared well with the optimum value of \( G = 0.179 \) for a cylindrical bore, square ended air core solenoid.

A Hall probe was used to measure the axial magnetic field which was within 5\% of the maximum value across the radius of the solenoid. Laser gas was introduced through one of the perspex end plates and exhausted through the other using a vacuum pump maintaining a pressure of 30 mb in the cavity. The maximum gas flow rate was limited by the capacity of the vacuum pump to 2.5x10\(^{-3}\) m\(^3\)/s. A d.c. welding power supply was used to supply a field current of up to 250 A corresponding to an axial magnetic flux density of 0.5 T. The electric discharge was supplied from a variable output transformer supplying a three phase high voltage transformer using full wave rectification. A discharge stabilising impedance of 10 kOhms was used to limit the maximum discharge current to 2.4 A.
Fig 6.9 Schematic diagram of rotating discharge equipment
Fig 6.10 Electrical circuit of rotating discharge equipment
Various techniques were considered to measure the speed of rotation of the discharge. Some optical methods can give erroneous readings due to persistence of luminosity. The low magnetic field associated with the relatively low currents of a glow discharge made measurement of the magnetic field with a probe difficult. A simple solution was to use a voltage probe inserted at the mid-point between the electrodes using a 1.6 mm diameter tungsten rod. The probe extended the full length of the coil so that the discharge always passed across the probe. An oscilloscope and frequency meter were used to detect the change in potential of the probe as the discharge rotated. The output of the probe was attenuated by 1000:1 and passed through a variable frequency bandpass filter to remove power supply ripple and high frequency (>10 kHz) airborne interference.

The rotating discharge is illustrated in Fig 6.11. The discharge current is identical in both photographs. The second photograph shows the dramatic effect on the discharge of applying an axial magnetic field of 0.04 T. The disturbance to the discharge caused by the voltage probe used to measure the rotational frequency can be seen clearly.

The magnetic flux density on the axis of the field coil is given by:

\[ B = kI_f \]

where \( B \) = magnetic flux density (T)  
\( I_f \) = field current (A)  
\( k = 2 \times 10^{-3} \) (calibration constant)
Fig 6.11 Photographs of (a) static and (b) rotating discharges
The maximum field obtained at the surface of the central anode was 0.5 T at a field current of 250 A.

The variation of discharge voltage with current is shown in Fig 6.12 under different conditions of magnetic flux densities. The zero magnetic field condition corresponds to a static discharge with a current of up to 1 A. The normal glow voltage increased with magnetic field by about 40% with a magnetic flux density of 0.025 T. The increase in discharge voltage is due to the higher electric field required to accelerate electrons across the magnetic field which tends to oppose the radial motion of the electrons travelling from cathode to anode. The higher discharge voltage is observed in both the glow and arc regime of the characteristic.

At zero magnetic field the glow to arc instability occurs at about 0.55 A. Further increase in discharge current results in a stable arc discharge with a correspondingly lower discharge voltage, the loss of the cathode glow, the formation of arc spots and a bright and constricted column (Section 4.6). When the magnetic field was applied the current at which the glow to arc transition occurred increased from 0.055 A at zero magnetic field to 2.4 A at 0.025 T. Offsetting the glow to arc transition enabled an increase in power input to the glow discharge from 250 W with zero magnetic field to 1530 W with a magnetic flux density of 0.025 T, representing a sixfold increase in discharge power.

At zero magnetic field as the discharge current is increased the cathode root expands over the cathode surface in the normal glow region until it covers the cathode surface and then in the abnormal glow the current density increases with the current. As the magnetic
Fig 6.12 Variation of discharge voltage for several conditions of magnetic flux density
flux density increases the rotational velocity increases and the
cathode root on the outer electrode starts to lengthen in the
circumferential direction whilst decreasing in width under the effects
of the axial divergence of the magnetic field and the rotational
forces on the discharge. The anode root changes shape corresponding to
the effect on the cathode, and the discharge column alters from an
approximately circular discharge to a shape similar to a rotating
segment of a circle. As the rotational speed increases the segment
formed by the discharge increases in size until the discharge gap is
filled. At these relatively low rotation speeds the discharge does
not rotate in its own wake as the decay time of the ionised states is
short compared with the period of rotation (1 ms).

The increase in current at which the glow to arc transition
occurred with applied magnetic field is considered to be due to the
improved uniformity of the discharge. The uniformity of the discharge
is improved through the turbulent interaction of the conducting
species in the positive column of the discharge with neutral gas
particles. The effect of the turbulence is to reduce the probability
of local low impedance, high temperature regions forming within the
plasma, which can lead to the propagation of incipient arcs
(streamers) within the discharge. The turbulence causes rapid
dispersion of arc streamers within the positive column by the highly
sheared rotational fluid flow before the arcs reach the anode. It has
been shown by Nighan (1972) that if the gas dwell time within the
discharge region is below 1 ms power densities of up to $10^5 \text{ mW/mm}^3$ can
be achieved. At rotational frequencies of 400 Hz the effective gas
dwell time of a discharge of approximately 20 mm diameter in any
region of gas is of the order of 0.2 ms. The only limit on discharge
current was the equipment available for the tests limiting the maximum
discharge current to 2.4 A, which represented a power density of 4.4 mW/mm$^3$. These results indicate that at quite moderate magnetic fields (0.075 T) high discharge power densities can be realised.

The variation of rotational frequency of the discharge with discharge current is shown in Fig 6.13. The variation is plotted for a number of different magnetic flux densities and illustrates the sensitivity of the rotational frequency to the magnetic flux density. Fig 6.14 shows the variation of rotational frequency of the discharge with magnetic flux density and shows the greater significance of the applied magnetic field to the rotational frequency at a number of constant values of discharge current. The dependence of the rotational frequency of the discharge on the magnetic flux density can be written in the form

$$f = B^p I^q$$  \hspace{1cm} (6.3)

where $2.56 < p < 2.88$

and $0.27 < q < 0.4$

These results indicate the greater dependence of rotational velocity on the magnetic flux density rather than on discharge current. This is likely since increase in current is accompanied by an increase in cross-sectional area of the discharge which will tend to increase the coefficient of drag. The value of $p$ is more than four times those reported for arc discharges at atmospheric pressure (0.55-0.65, Harry et al 1968) however the effect of operation at low pressure may account for this.

The variation in discharge voltage at low and high magnetic flux
Fig 6.13 Variation of discharge rotational frequency with discharge current
Fig 6.14 Variation of rotational frequency of discharge with magnetic flux density
densities is shown in Figs 6.15 and 6.16. As the magnetic flux density was increased a rise in discharge voltage was observed. The effect of the axial magnetic field is to increase the path length of the electrons travelling from the cathode to the anode resulting in an increase in the discharge voltage in both the glow and arc regimes. An abrupt increase in discharge voltage occurred at magnetic flux densities of approximately 0.017 T; the discharge voltage then continued to rise with increasing magnetic field. The glow discharge was apparent both above and below the observed voltage discontinuity. At this discontinuity the signal from the voltage probe used to indicate the rotation of the discharge, changed from a pulsed signal to a constant voltage and the positive column of the discharge changed from a short glow about 10 mm long adjacent to the cathode fall region to a fully developed column extending to the anode fall region. The magnetic field flux density at which this discontinuity occurred increased with higher discharge currents.

The presence of the probe might be expected to affect the discharge and in particular the onset of the glow to arc transition. To investigate this a series of voltage and current measurements were made with and without the probe in position which indicated that the probe had no effect on glow discharge stability. The voltage probe used to measure the rotational speed was used up to rotational frequencies of more than 1600 Hz without any deterioration of the signal from the voltage probe. The lowest value of velocity at which the voltage discontinuity occurred was about 1100 Hz, Fig 6.14, which is well within the frequency range of the voltage probe. The conclusion from this is that the voltage discontinuity occurred within the discharge and is not due to the probe behaviour. One possible explanation of the discontinuity is that the glow discharge is
Fig 6.15 Variation of discharge voltage with magnetic flux density at low magnetic fields ($B < 0.05 \text{T}$)
Fig 6.16 Variation of discharge voltage with magnetic flux density at high magnetic fields ($B<0.5$ T)
trailing in its own wake of previously ionised gas. Under these conditions an azimuthal current may be expected to flow under the influence of the axial magnetic field and the discharge ceases to rotate as a spoke which would be expected to cause an increase in the discharge voltage as observed.

A test was conducted to observe the effects of reversing the polarity of the electrodes on the behaviour of the discharge. The outer anode was earthed to prevent electrical breakdown to the field coil. The resulting discharge was very unstable and subject to large fluctuations in discharge current. The discharge became more stable at higher magnetic fields. The fluctuations in current appeared to correspond to the movement of the negative glow around the central cathode. The relatively small area of the anode glow was extended around the anode surface in a manner corresponding to the instantaneous position of the negative glow. A very short positive column existed extending only 10 mm from the negative glow. The length of the positive column was independent of both discharge current and magnetic flux density. A 60% reduction in discharge current was observed for an increase in magnetic flux density of 0.04 T compared with less than 5% reduction for the same change in flux density with a central anode and outer cathode. The rotational frequency of the discharge was lower for a given discharge current and magnetic flux density than with the original polarity configuration. A frequency of 40 Hz was detected at a discharge current of 125 mA and a magnetic flux density of 0.02 T compared with 610 Hz for the same conditions with the other configuration. Reversal of the field coil with polarity resulted in a vast improvement in discharge stability. The discharge had the same appearance as earlier but was not subject to the large fluctuations in current previously recorded.
The velocity profile developed by Capjack et al. (1981) indicates a maximum velocity near the midpoint between the electrodes which is not consistent with a continuously rotating discharge. For a continuous discharge, when the discharge is not rotating in its own wake, the velocity of the discharge must vary with the radius and the highest velocity must always be at the root on the outer electrode. A further test was carried out at a gas pressure of 53 mb and a magnetic flux density of 0.073 T under the same conditions as Capjack et al. (1981). Under these conditions the highest value of current at which a glow could be maintained was 0.78 A. At currents above this the discharge became constricted, the uniform cathode glow could no longer be seen, and the discharge became highly luminous. Arc spots were visible on the electrodes and the transition was also accompanied by an audible output also reported by Capjack et al. (1981) at about 10 kHz but characteristic of rotating arcs. Subsequent examination of the cathode surface indicated the characteristic erosion tracks associated with arc roots rather than a glow discharge. Further increase in the magnetic field to 0.5 T did not cause the discharge to revert to a glow. At the same time the discharge voltage decreased abruptly accompanied by an increase in discharge current typical of a glow to arc transition. Although the gas mixtures are not the same the higher N₂ and CO₂ content used by Capjack et al. should result in a higher discharge voltage and lower glow to arc transition current. The difference in the discharge current at which the glow to arc transition occurred, 2.4 A at 0.025 T and 0.78 A at 0.5 T, may be explained by the difference in pressure 27 mb and 54 mb respectively.

Glow discharge currents of up to 2.4 A have been achieved by rotating the discharge in a magnetic field. The increase in discharge
current before the glow to arc transition occurs represents a four fold increase over the non-rotating discharge. The voltage across the discharge is also increased by about 40% in the magnetic field and the highly turbulent fluid flow of the discharge medium. The increase in discharge current and voltage represents an increase in discharge power of around six times the non-rotating discharge power.

The results have shown the greater dependence of the rotational frequency on the magnetic flux density rather than the discharge current and that the value of $P$ (from equation 6.3 where $f = B^P_1^q$) is around four times larger than for previously reported values for atmospheric arc discharges.

The results reported by Seguin et al (1981) and Capjack et al (1981) of glow discharges operating at 10 A were not repeatable here even with magnetic flux densities of more than five times those used previously. The results here suggest that Seguin et al and Capjack et al observed a low pressure arc discharge rather than a glow discharge at the higher discharge currents reported.

Although the investigations have demonstrated the feasibility and potential of this technique for producing uniform high power glow discharges, the technique does not appear to be particularly well suited to fast axial flow lasers for two reasons. First the axial component of gas velocity is high (typically 300 m/s) compared to the rotational velocities measured in the rotating discharge equipment (approximately 200 m/s) thus causing low frequency spiralling of the discharge column downstream. Secondly, maintenance of high magnetic flux densities over the large volumes associated with the anode assemblies in fast axial flow lasers is difficult. The technique
appears to be more suited to a transverse laser arrangement utilising a coaxial cavity (Casperson and Remero 1973, Cheng and Casperson 1979) similar to the discharge equipment developed here. For these reasons, coupled with the very effective results obtained by injecting gas directly into certain regions of the fast axial flow discharge described in the next section, no further investigations into the rotating discharge were pursued.
6.4 GAS INJECTION SYSTEM

6.4.1 High Pressure Gas Techniques

The differential pressure available from the vane axial fan limited the range of techniques which may be applied to create the turbulent flow required for operation of an unconstricted high power glow discharge. The aerodynamic mixing techniques investigated (Section 6.2) demonstrated that larger pressure drops were needed to create the necessary level of turbulence than were available from the two-stage vane axial fan system.

The magnetic coupling of the glow discharge (Section 6.3) demonstrated the feasibility of this technique for producing high power unconstricted glow discharges. It was also shown that the magnitudes of magnetic flux density and radial component of discharge current required to obtain a uniform discharge were difficult to obtain within the geometry and discharge current range of the fast axial flow laser.

The following investigations use a separate high pressure gas supply (from a compressed gas cylinder) to inject additional gas into the vacuum recirculating system. This mode of operation overcomes the limitations of the low pressure head (about 2 mb) available from the vane axial fan and enables a wider range of techniques to be explored using the high pressure head (20 bar) now available. The large volume flow rate of gas recirculated by the vane axial fan is used to remove most of the heat from the laser cavity while the high pressure gas flow is used primarily to generate turbulence within the discharge region. This technique also enables turbulence to be generated selectively in different regions of the discharge by introducing gas.
at different points in the laser cavity.

A series of tests were carried out to investigate the effect of injecting high pressure jets of gas into the low pressure glow discharge. Flow rates of up to 0.006 kg/s at pressures of up to 20 bar were directed into the discharge using metal nozzles mounted in a fabricated pyrex glass discharge tube with a number of radial ports. Up to three nozzles were used simultaneously at three positions along the discharge tube over a range of angles and flow rates. The injected gas resulted in large scale motion of the positive column in the tube with an increase in column diameter of only 5% at discharge currents between 1-2 A. Gas was also directed at both the upstream and downstream ends of the discharge with no improvement in discharge uniformity.

A gas jet directed at the anode rod resulted in a change in diameter of the discharge column (Fig 6.17(a)). The column diameter increased by approximately 50%, but the anode root tended to move to the downstream side of the gas flow reducing the effectiveness of the applied jet. Gas was then injected through an off-axis aperture near the anode root (Fig 6.17(b)). The positive column did not become diffuse but moved around in the discharge tube in an unpredictable manner. The electrode was modified to provide a coaxial flow of gas around the anode rod (Fig 6.17(c)) and the discharge column became more controllable and diffuse downstream. The discharge ceased to move unpredictably in the tube and the anode root stabilised on the circumference of the anode root. A laser output of 125 W was obtained at a discharge current of 500 mA at an electrical to optical efficiency of 6%. As the pressure of the injected gas was increased the anode root stabilised at the base of the anode rod, out of the
Fig 6.17 Initial stages of development of the gas injection electrode
flow of injected gas and the discharge again became constricted. The root moved to the base of the anode as a result of the interaction of the self-magnetic fields associated with the current in the electrode and the discharge which caused the root to be driven to the base of the anode rod. A profiled pyrophyllite nozzle was constructed (Fig 6.17(d)) to try to improve the interaction of the gas flow with the anode fall region. Over the entire range of pressures and flow investigated a small thin jet of plasma was ejected from the nozzle leaving the main positive column unaffected by the injected gas. A number of rod positions were tried ranging from the rod submerged in the nozzle to protruding 30 mm from the front of the nozzle.

A copper pipe anode was successfully used to produce a uniform column (Fig 6.17(e)) but after approximately 30 seconds conditioning of the cut edge resulted in the anode root moving from the end of the pipe to its outer diameter. An insulating pyrophyllite shroud was used to force the anode root to remain in the injected gas flow (Fig 6.17(f)).

From all the configurations investigated the following points became apparent:

1. to obtain uniform distribution of the positive column injection of gas at the anode root and fall region was most effective.
2. the anode root always moves to a position of lowest pressure away from the path of the flowing gas.
3. the flowing gas should be injected parallel with the discharge region adjacent to the anode fall to achieve maximum effect.

Further anodes were designed using perforated plates and nozzles
surrounded by electrical insulators to constrain the anode root in the gas stream. Initially the anodes were made of silver steel plates 5 mm diameter, 2 mm thick, into which a number of 0.5 mm diameter holes were drilled. The effect of this was the anode root located in the area between the holes and was largely unaffected by the gas which flowed around it. When a fine stainless steel mesh was substituted for the porous plate the gas flow passed through the anode root which now spread over several holes. The change in behaviour of the positive column was dramatic, with the positive column very stable and uniform, completely filling the glass discharge tube.

The relative effects of the recirculating gas and the injected gas were compared and it was found that the recirculating system could be omitted with no fall-off in laser output power (about 125 W) provided a sufficient mass flow rate was injected through the anodes. For this reason the vane axial fan recirculating system was disconnected, gas was supplied solely through the injection anodes and the laser was operated for brief periods (<10 s) as a high pressure blow-down system.

In the following section the operational characteristics of the gas injection anodes are determined in the blow-down laser system.

6.4.2 Gas Injection Anodes

The previous series of tests demonstrated the need to confine the anode root and fall region in the injected gas flow. The tendency of the anode root to move away from the flowing gas towards a lower pressure region excludes the use of a solid rod placed in the gas flow. A mesh through which gas is injected minimises the areas of
relatively static gas immediately downstream of the anode surface, thus subjecting the root and fall region to the most turbulent flow conditions. The high Reynolds number flow regimes (>15000) associated with the gas flowing through the anode surface have not been possible with the previous flow conditioning techniques investigated using a range of profiled solid anodes. The solid anode always has stagnation regions associated with it immediately downstream which appear to be deleterious to the operation of a uniform glow discharge. The separate gas feeds associated with each gas injection anode also enable the production of a highly turbulent flow in the discharge column to be sustained, further enhancing the uniformity and stability of the glow discharge.

Injecting large amounts of gas into the evacuated laser produced a rapid rise in pressure of the system, the rate of rise of pressure being proportional to the mass flow rate of the flowing gas. The flow rates required to convectively remove the heat from a high power CO₂ laser are of the order of 0.008 kg/s of gas per kilowatt of laser output. At a pressure of 40 mb and temperature of 200 °C this corresponds to a volume flow rate of 0.93 m³/s (3350 m³/h). This flow rate is vastly in excess of the pumping capacity of rotary vane vacuum pumps. The combined pumping speed of the pumps available was 0.025 m³/s (90 m³/hr), which was insufficient to maintain constant pressure conditions within the laser cavity during a test. A large gas receiver was installed measuring 2 m diameter by 4 m high which was evacuated to extend the duration of tests at high gas flow rates. The receiver was connected directly to the 300 mm diameter stainless steel pipework of the recirculating system. The volume of the gas receiver was 9.6 m³ and the period of operation over the pressure range of interest (10-50 mb) by eighteen times. At high gas flow rates (up to
0.04 kg/s) tests lasted less than 3 s. The computer data logging system enabled all the required data to be recorded during these brief tests.

The gas injection anode consisted of a stainless steel mesh 0.3 mm thick with 0.25 mm diameter holes on 0.36 mm centres with a transmission of 48% positioned in an electrically insulating pyrophyllite nozzle. The nozzle was mounted at one end of a copper pipe through which the laser gas was passed. The copper pipe was electrically insulated with a layer of plasma sprayed alumina to prevent unwanted attachment points of the anode root. The mesh was recessed in the nozzle to ensure good interaction of the flowing gas with the anode root and fall region. The gas injection anode is illustrated in Fig 6.18.

![Diagram of the gas injection anode](image)

**Fig 6.18** The gas injection anode.

A single gas injection anode was operated at a gas flow rate of 0.0083 kg/s and the discharge current repeatedly adjusted to give the
maximum power through the operating range of pressure at this flow rate. The results for the single gas injection anode are shown in Fig 6.19(a). The graphs are plotted to a base of pressure which is also linearly proportional to time, each point representing 600 ms. A maximum laser output of 663 W was obtained at a pressure of 20 torr and an electrical to optical efficiency of 12%. The variation of the discharge voltage and current with gas pressure is shown in Fig 6.19(a). The voltage rises linearly with pressure due to the increase in electron losses as the gas density rises with pressure. This results in an increase in the electric field strength sustained across the gas. The rise in electric field strength is a contributory factor to the onset of the glow to arc transition which has been observed to occur at lower currents at elevated gas pressures. The rise in electric field strength does not cause a proportionate rise in the E/N ratio since the rising pressure causes a disproportionate rise in the neutral particle density. The near optimum value of E/N of 1.1x10^-16 V.cm^2 exists at a cavity gas pressure of 46 mb.

The discharge current falls linearly with pressure due to the constant supply voltage condition which exists through the test. The average electrical discharge power increases by 20% through the test (Fig 6.19(b)). The laser power is at a maximum between 26-33 mb because of the higher gain which occurs in the lasing medium at these pressures. The maximum laser power does not therefore necessarily occur under the conditions of either maximum input power, optimum E/N or optimum power loading of the gas. The fall off in laser power is similar to the characteristic shape of laser gain versus gas pressure curves determined by Deutsch (1967). The reduction in gain is most likely to be due to the increase in gas pressure rather than discharge current since the decrease in gain with increasing discharge current
Fig 6.19 Performance of single gas injection anode
(a) variation of discharge voltage and current with gas pressure
(b) variation of laser and electrical power with gas pressure
is less pronounced for large diameter tubes (Hill 1972).

A range of stainless steel meshes were investigated with transmissions ranging from 17% to 48%, all meshes were 0.25 mm thick. The behaviour of the electric discharge seemed unaffected by the variation in mesh transmission except for a secondary effect caused by the reduction in gas flow rate as the transmission was reduced. When the gas supply pressure was increased to compensate for this reduction in flow rate the discharge behaved as before. All subsequent tests with meshes were carried out with the 48% transmission mesh to minimise the gas pressure drop and maximise the available mass flow rate from the system.

Even with a single gas injection electrode the power per unit length is 1100 W/m which compares with only 666 W/m for the Control 2 kW Mk 2 fast axial flow laser.

The sensitivity of the discharge uniformity to electrode and column conditions.

The improvement in discharge uniformity with the use of the gas injection anode has been demonstrated. The uniformity and stability of the discharge is dependent upon both the electrode and column conditions. A series of tests were conducted to investigate the relative effects of these two conditions.

A single gas injection anode was placed on the axis of the discharge tube with a wire placed 20 mm from the nozzle (Fig 6.20). The electrical connection was made first to the wire anode and then to the gas injection anode. The gas flow rate was varied and the current
at which constriction of the discharge column occurred recorded for both the gas injection anode and the single wire anode.

The onset of arcing was also monitored using an oscilloscope connected to a transformer monitoring the total discharge current. The onset of arcing was accompanied by instability in the current waveform. The variation of the current at which instability occurred with gas flow rate is shown in Fig 6.21. The graph illustrates the effectiveness of the gas injection anode of raising the current at which constriction of the discharge column occurs compared with when a single wire is used as an anode positioned near the gas flow nozzle over the range of gas flow rates investigated.

Fig 6.20 A gas injection anode with a wire anode positioned 20 mm from the gas nozzles.

The turbulence developed by the anode jet in the discharge column region was the same in both cases. The test therefore indicates the importance of injecting gas in the anode root and fall regions. A maximum stable glow discharge current of 1.25 A was obtained at a gas
Fig 6.21 Variation of discharge current at which arcing occurred with gas flow rate
flow rate of 0.0062 kg/s. The results also indicate that the effectiveness of the anode jet in developing a turbulent flow field is such that even a single wire anode placed 20 mm to one side of the nozzle can be used to sustain stable glow discharge currents of up to 0.65 A. This compares favourably with other fast axial flow lasers typically operating at between 0.15 and 0.3 A per discharge tube at equivalent flow rates. The discharge associated with the wire anode was slightly constricted for approximately 20 mm downstream of the anode where it was not in the turbulent gas flow, after which it became entirely uniform and free from streamers. The advantage of the gas injection anode is not only the ability to sustain high stable discharge currents but also that none of the downstream region is wasted through arc formation.

The dependence of the discharge stability on the position of the wire anode in relation to the gas jet was investigated. The wire anode was moved in increments of 5 mm from the nozzle of the gas injection anode and the current at which arc streamers formed in the discharge recorded for a constant gas flow rate. The flow conditions in the discharge tube were the same throughout the tests. The variation of this current with linear displacement of the wire from the nozzle is shown in Fig 6.22 at a gas pressure of 24 mb and a gas flow rate of 0.004 kg/s. The first point on the graph at $l=0$ corresponds to the condition where the electrical connection is made to the stainless steel mesh in the anode. All other points correspond to the electrical connection being made to the wire anode only. The initial fall off in current with displacement highlights the importance of the gas flow in the anode root and fall regions. As the anode is progressively moved further from the gas nozzle the maximum stable operating current decreases. It was not possible to maintain
Fig 6.22 Variation of discharge current at which arcing occurred with distance of wire anode from gas injection anode.
the anode root directly in the flow of gas by positioning the wire across the gas jet. The root was always blown along the wire out of the flowing gas resulting in discharge collapse and instability in the anode region.

Multiple Gas Injection Anodes

The characteristics of three gas injection anodes were investigated over a range of gas flow rates and were compared with the earlier results for a single anode. The three anodes were supplied from a single gas manifold and a cylinder of laser gas via variable area flow meters and a remotely operated solenoid valve. A program was written for the HP41 computer to calculate the mass flow rate of gas and the relative flows for the conditions of pressure and flow readings occurring for all the different configurations investigated.

The laser output power was determined for a range of gas flow rates. The graph in Fig 6.23 compares the variation of laser output power with gas flow rate for the single and multiple anodes configuration. The electrical power was adjusted for each flow condition to maximise the laser output power. The multiple anodes consistently developed a higher laser output over the range of flows investigated. The difference in performance becomes more apparent at higher discharge powers where the current associated with the three individually stabilised anodes is still sufficiently low to remain uniformly distributed by the injected gas. The maximum total discharge current is now equal to a multiple of the maximum stable current associated with each of the single anodes operating at the limit of unconstricted operation. The utilisation of the cavity in the anode region is greatly improved with the multiple anodes because
Fig 6.23 Variation of laser output power with gas flow rate

(a) single gas injection anode  (b) three gas injection anodes
of the branching of the discharge into separate transition regions attached to each anode. This provides an axially symmetric distribution of plasma in contrast to the single anode configuration where the plasma is distorted toward one side of the cavity in the anode transition region (see Fig 3.6 for Control Laser arrangement). The use of the multiple gas injection anodes enables a more turbulent flow field to be developed in the column region of the discharge because of the multidirectional flow of gas entering the laser cavity. The additional interaction of these jets enhances the turbulence in the laser cavity improving the uniformity of the discharge column.

The maximum laser power was found to scale linearly with the mass flow rate of injected gas. This is primarily due to the increased total thermal capacity of the gas to convectively remove the power dissipated in the discharge which then lowers the operating temperature of the lasing medium. Thus for a specific operating temperature a greater power input can be sustained. Secondly the velocity of the gas through the discharge increases with both mass flow rate and total discharge power. At high discharge powers the compressible gas expands with the addition of thermal energy and therefore leaves the constant diameter discharge tube at a higher velocity (Section 2.5). The increase in velocity reduces the dwell time of the gas in the cavity which enables higher specific power loadings to be sustained as any incipient arcs are swept downstream before they cause catastrophic collapse of the glow column. The mass flow rate was highest for the multiple anodes because of the higher conductance of the gas flow path from the manifold to the cavity entrance.

The electrical to optical efficiency was on average over the
range of tests between 0.5-1% higher for the multiple gas injection anodes. Although this increase represents only a 5-10% rise, in laser power, the maximum laser power that could be developed with the three gas injection anodes was increased by 21% for the same gas flow rate (0.0083 kg/s).

The previous tests have demonstrated the importance of introducing the gas in the anode fall region; the following test investigates the effect of changing the flow conditions in the discharge tube whilst maintaining the same total gas flow rate. The tests were carried out with and without the nozzles attached to the gas injection anodes thus changing the way the gas entered the discharge tube from $45^\circ$ to radially from the anode head.

The gas injection anode is shown connected in Fig 6.24(a) with the gas flow shown schematically flowing into the laser cavity at an angle of $45^\circ$. The second arrangement is illustrated at the top of the
anode head in Fig 6.24(b) where the nozzle assembly has been removed from the electrode and the gas flows directly out of the brass body of the electrode radially into the laser cavity. The electrical connection was made to three other gas injection anodes which were isolated from the gas supply and merely acted as convenient conduction points. Three anodes and three gas feeds were used in the test carried out at a gas flow rate of 0.0075 kg/s. The electrical power was repeatedly adjusted to obtain the maximum laser output power with an unconstricted discharge. The variation of laser power with gas pressure is shown in Fig 6.25. A maximum laser power of nearly 1100 W was obtained with the three gas injection nozzles at a maximum discharge current of 1.65 A (curve (a)). The discharge remained stable and uniform over the entire pressure range of the test. The nozzles were then removed and the gas allowed to flow radially into the anode head and then into the discharge tube. The exit velocity of the gas from the nozzles and electrode bodies was the same in both tests. This test changes the method of introducing gas to the cavity by removing the nozzles previously used and allowing the gas to enter radially from the anode head into the discharge tube. The gas flow rate was kept the same as for the previous tests but the flow field in the discharge tube should now be quite different to determine the importance of the flow field rather than simply flow rate in the discharge tube. The improvement in discharge uniformity can be clearly seen in the photographs in Fig 6.26. The discharge is compared with the gas feeds separate from the anodes (Fig 6.26(a)) which is constricted along its entire length. The second photograph (Fig 6.26(b)) shows the discharge with gas injection anodes completely filling the discharge tube with a high degree of uniformity, good stability and an average gas temperature of about 150 °C. The discharge current was 1.4 A and gas flow rate 0.0075 kg/s in both
Fig 6.25 Variation of laser output power with cavity gas pressure for different gas flow configurations
Fig 6.26 Photographs showing the improvement in discharge uniformity with gas injection anodes

(a) gas feeds separate from anodes

(b) gas injection anodes
photographs. At the same electrical settings a highly constricted and unstable discharge resulted with a maximum laser output of 750 W (Fig 6.25 curve (b)). The discharge current was then reduced until a uniform glow discharge was developed (Fig 6.25 curve (c)). This reduced electrical input power produced a maximum laser power of 355 W at a discharge current of only 0.57 A. These tests demonstrate the effectiveness of the method of introducing gas via the nozzles into the laser cavity showing that at the same gas flow rate the discharge current could be raised from 0.57 A to 1.65 A corresponding to an increase in laser output power from 355 W to nearly 1100 W, representing a three fold increase. The test also shows that although the laser output power should scale with the mass flow rate of gas according to thermodynamic principles, this is only true when sufficient turbulence exists in both the anode fall and discharge column regions to maintain a uniform glow discharge.

The effects of increasing the number of gas injection anodes

A maximum laser output of 1220 W has been achieved with three gas injection anodes. This maximum power appeared to be limited only by the available mass flow rate of gas injected into the discharge. A new anode head (Fig 6.27) was constructed to accommodate up to twelve gas injection anodes and three auxiliary gas feeds to increase the maximum gas flow rate. The flow rate of gas was increased by improving the design of the gas supply system to reduce pressure drops from the cylinder supply, installing a high flow rate regulator, and increasing the number of gas injection anodes. An auxiliary gas supply was installed using a separate cylinder, flow meter solenoid valve, manifold and three gas nozzles. These measures enabled gas flow rates of up to 0.029 kg/s to be achieved, nearly three times the
Fig 6.27 Anode head with twelve gas injection anodes
previous flow available. A schematic diagram of the new gas flow system is shown in Fig 6.28. The gas flow reading was recorded at pressures above 1 bar on the downstream side of the flow meter to reduce errors and then corrected for gas composition and operating pressure. The solenoid valves were required to turn the flow of gas on and off rapidly at high gas flow rates. At a flow rate of 0.0284 kg/s the laser output was limited to only five seconds because of the rapid rise in cavity pressure. The increase in laser output power with additional gas injection anodes is summarised in Table 6.8.

<table>
<thead>
<tr>
<th>Number of anodes</th>
<th>Laser Power (W)</th>
<th>Gas flow rate (kg/s)x10</th>
<th>Laser power loading of gas (kW/kg/s)</th>
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<tr>
<td>1</td>
<td>663</td>
<td>8.3</td>
<td>80</td>
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<td>3</td>
<td>1220</td>
<td>12.6</td>
<td>89</td>
</tr>
<tr>
<td>9</td>
<td>1987</td>
<td>15.2</td>
<td>131</td>
</tr>
<tr>
<td>12</td>
<td>3850</td>
<td>28.4</td>
<td>136</td>
</tr>
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</table>

Table 6.8 Summary of the performance of increasing numbers of gas injection anodes.

The increase in laser power output from 663 W to 3850 W represents a near sixfold increase compared with the increase in gas flow rate of just over three times. The rise in laser output is clearly not due solely to the additional gas flow since the table also shows that there was a rise in the specific laser power loading of the gas of 1.7 times. The rise in specific laser power loading of the gas can be explained in terms of the following. Firstly the utilisation of the cavity in the anode region is clearly improved with more anodes since the volume of the dead space between the anodes where little or no plasma exists is reduced. As the number of gas injection nozzles increases the complexity of the flow field downstream increases resulting in more turbulence and higher local velocities in the discharge tube. The reduction in the gas dwell time in the discharge
Fig 6.28 Schematic diagram of the new gas injection flow system.
tube for cold flow conditions is from 7.4 ms to 2.1 ms. As this dwell time is reduced so the power loading of the gas may be increased since streamers formed in the column tend to be convectively removed before leading to catastrophic collapse of the discharge column. The actual dwell time is shorter than the figures calculated here since the effect of heat input is to expand the compressible gas and accelerate it to higher velocities. This is discussed more fully in Chapter 7.

A summary of the operational parameters of the laser is given in Table 6.9.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
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<td>Discharge voltage (kV)</td>
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</tr>
<tr>
<td>Discharge current (A)</td>
<td>1.8</td>
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<tr>
<td>Laser Power (kW)</td>
<td>3.85</td>
</tr>
<tr>
<td>Electrical to optical efficiency (%)</td>
<td>21</td>
</tr>
<tr>
<td>Gas pressure (mb)</td>
<td>43</td>
</tr>
<tr>
<td>Gas flow rate (kg/s)</td>
<td>0.0284</td>
</tr>
<tr>
<td>Gas exit temperature (°C)</td>
<td>230</td>
</tr>
<tr>
<td>Electrical power loading of gas (kW/kg/s)</td>
<td>646</td>
</tr>
</tbody>
</table>

Table 6.9 Operating parameters the laser at an output power of 3.85 kW

A reduction in the current associated with each anode occurs as the number of anodes is increased. This reduction in the current in the transition region between the anode and the fully developed column reduces the self-magnetic constrictive forces and results in better distribution of the discharge through the action of the aerodynamic
forces. The lower current at each anode also reduces the tendency of the glow to burn the pyrophyllite caps and destroy the stainless steel mesh.

6.6 SUMMARY OF RESULTS

A high flow rate gas recirculating system enabled a study to be carried out of the interaction of multiple glow discharges with high velocity turbulent gas flows. A range of aerodynamic techniques was explored to develop a stable, uniform glow discharge at high electrical power inputs. The techniques applied to develop turbulence were restricted by the available pressure head of the vane axial fan which limited the amount of turbulence which could be generated in the discharge region.

Turbulence within the discharge was enhanced by using an external magnetic field to rotate the glow discharge within the laser cavity. This technique was then studied in detail in a test rig to investigate the range of parameters required to produce a high power, uniform glow discharge. A sixfold increase in discharge power was achieved using magnetic flux densities of up to 0.5 T. A previously unreported discontinuity was discovered in the discharge voltage-current characteristic and a model explaining its presence described. The work also highlighted inconsistencies of work previously reported in the literature using a magnetic field to rotate a glow discharge.

The differential pressure constraints of the gas recirculating system were overcome by using an external source of gas injected into the laser which enabled new methods of creating turbulence within the
discharge to be developed. Gas was injected in various regions of the discharge but the anode fall region was found to be most sensitive to the gas flow and a range of configurations combining the anode with a turbulent gas flow investigated. The gas injection anode resulted in a dramatic improvement in discharge stability and uniformity enabling glow discharges of up to 134 mm dia and discharge currents of up to 2 A to be operated. The relative effects of changing the position of the anode root with respect to the gas flow and changes in the flow conditions in the column region were investigated. Multiple gas injection anodes were tested and the dependence of the discharge stability and laser output power determined over a range of conditions of gas flow rate, pressure, number of electrodes and electrode geometry. Twelve gas injection anodes were used in a blow-down laser system which developed a laser output power of 3.8 kW (for around 2 s) at an electrical to optical efficiency of 21% from a single discharge tube only 600 mm long by 93 mm dia.

The work described in this chapter has been published or submitted for publication as detailed below:

(1) HARRY, J.E., EVANS, D.R., 'A high power compact axial flow CO₂ laser', (Submitted for publication J. Quant. Elec., August 1986).
(3) HARRY, J.E., EVANS, D.R., 'Magnetic stabilisation of a rotating glow discharge', (Submitted for publication J. Appl. Phys., March
7.1 TRANSITION FROM THE BLOW-DOWN TO THE GAS INJECTION RECIRCULATING SYSTEM.

A laser power output of 3.85 kW was achieved for about 2 s with the blow-down laser system described in Section 6.4. The operation of a high power CO₂ laser in this open-cycle mode is neither economical or useful for continuous materials processing applications. This chapter describes the implementation of the multiple gas injection technique to a recirculating laser and the investigations carried out on the continuous output laser.

The important differences in design and operation between the two systems may be divided into two categories; those associated with the change in available pressure head to recirculate the gas and those associated directly with problems of recirculating the same gas repeatedly around the laser system.

The reduction in available pressure head to deliver the gas to the laser head with a Roots pump gas recirculating system is considerable. Pressurised gas cylinders could be operated at pressures in excess of 20 bar and Roots pumps at only 0.2 bar. This corresponds to a 100 fold decrease in gas density and proportionate rise in volume flow rate required. The increase in volume flow rate of the gas delivered to the laser head requires lower conductance flow paths constructed from larger diameter pipework. The pressure drops associated with the pipework used to return the flowing gas to the pumping system are even more critical than the delivery pipework because of the low static pressure in this region and careful design
is required to ensure adequate throughput of gas. The velocity of the
gas through the nozzles will also change because of the changes in
volume flow rate and the necessary changes in nozzle diameter to
maintain acceptably low pressure drops through the system. The
methods of flow measurement must also be changed to one which impedes
the flow to a lesser extent than variable area flow meters.

One problem associated with recirculating the laser gas is that
of removing the heat dissipated in the gas flowing through the electric
discharge. The heat exchangers are required to have low pressure
drops and to cool the gas from approximately 280 °C to less than 30 °C.
The problems associated with atmospheric contaminants into the vacuum
system become critical with the recirculating system because of the
absence of fresh gas continually supplied to the electric discharge.
The leak tightness of the system is therefore more important than with
the blow-down system.

7.2 DESIGN AND CONSTRUCTION OF LASER
7.2.1 Laser Gas Recirculating System

The requirements of a continuous gas recirculating system for a
laser output power of 5 kW were defined from the results obtained from
the blow-down system in Chapter 6. The mass flow rate requirement was
based on the figure 0.007 kg/s per kilowatt of laser output determined
for the multiple gas injection anode arrangement investigated in
Section 6.4. A laser cavity gas pressure of 30 mb was selected as a
minimum pressure to combine a practical working density of the gas
with high mass flow rates and good electrical to optical efficiency.
The gas delivery pressure then becomes determined by the number of
stages of compression in the recirculating system. The gas
recirculating system was designed to be a flexible system enabling
operation of the laser over a wide range of experimental conditions in order to be able to investigate and optimise the gas injection technique under steady state conditions.

A high flow rate two stage gas recirculating system was built to compress and recirculate gas around the laser and to remove the heat from the lasing medium. A two stage system was necessary to achieve high gas compression ratios at flow rates of around 0.035 kg/s. The system comprised three Roots pumps (two in parallel and one in series), five heat exchangers, interconnecting pipework, bypass valves and control equipment. The general arrangement is shown in Fig 7.1 and a photograph of the complete recirculating system is shown in Fig 7.2.

The operational characteristics of the gas recirculating system are summarised below in Table 7.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas inlet pressure (mb)</td>
<td>30-60</td>
</tr>
<tr>
<td>Gas outlet pressure (mb)</td>
<td>160-240</td>
</tr>
<tr>
<td>Mass flow rate (kg/s)</td>
<td>0.010-0.040</td>
</tr>
<tr>
<td>Maximum heat removal (kW)</td>
<td>25</td>
</tr>
<tr>
<td>Maximum gas inlet temp (°C)</td>
<td>300</td>
</tr>
<tr>
<td>Maximum gas outlet temp (°C)</td>
<td>30</td>
</tr>
<tr>
<td>Gas mixture (by vol)</td>
<td>82% He:13.5%N2:4.5%CO2</td>
</tr>
<tr>
<td>Vacuum leak rate (mb.l/s)</td>
<td>&lt;10^-7</td>
</tr>
<tr>
<td>Drive motors (kW per motor)</td>
<td>15</td>
</tr>
<tr>
<td>Total water cooling</td>
<td>120 l/min @ 5.5 bar</td>
</tr>
</tbody>
</table>

Table 7.1 Operational Characteristics of Gas Recirculating System.
Fig 7.1 Schematic diagram of the gas recirculating system

Fig 7.2 Photograph of the gas recirculating system
The first stage consists of the two primary gas heat exchangers followed by two Edwards High Vacuum EH4200 Roots pumps each in parallel with the gas flow to achieve the required mass flow rate. The first stage of pumping operates at a compression ratio of between 2:1 and 2.5:1. The compression ratio of the pumps is limited by the heat of compression of the gas which is dissipated partly within the pump and also by the power available from the drive motors. All of the pumps incorporate special shaft oil seals and differentially pumped gearboxes to minimise oil contamination of the laser gas. The stators and rotors of the pumps were nickel plated to further reduce contamination of the laser gas. The primary gas heat exchangers remove the heat from the laser gas which has been heated to approximately 240 °C in the discharge.

The gas is cooled to 30 °C before entering the Roots pumps. The pressure drop on the gas side of the primary heat exchangers must be small because of the low pressure of the flowing gas. High differential pressures across these heat exchangers seriously reduce the flow through the laser. The pressure drop was reduced to 0.2 mb at rated gas flow rate and pressure. The interstage and second stage heat exchangers remove the heat of compression of the gas after each Roots pump.

The second pump stage consists of a single Edwards High Vacuum EH4200 Roots pump and heat exchanger. The second stage pump operates at a lower compression ratio of 2:1 because of the high density of the gas and consequently higher power associated with the heat of compression.
Two bypass valves were incorporated in the recirculating system (Fig 7.1) to enable the pressure loadings of each stage to be adjusted for optimum utilisation of the pumps. The valves also enabled a 70% reduction of the mass flow rate to be achieved whilst operating at constant laser cavity pressure.

The gas recirculating pumps and heat exchangers were water-cooled using mains water fed via a 250 litre break-tank and a high pressure water pump which supplied up to 125 l/min at 6 bar pressure.

7.2.2 Flexible Gas Couplings to Laser Head

The compact laser head permits modular construction of the laser system and remote operation of the laser from the gas recirculating system. This is possible because of the high power per unit lengths of discharge obtained using the gas injection anodes. Flexible gas pipes are used to connect the laser head to the gas pumping system and enable it to be moved independently of the pumps.

A computer program "PIPE CONDUCTANCES", (Edwards High Vacuum 1986) was used to solve the compressible fluid flow equations for high velocity gas flow within the flexible gas pipes. The equations were solved to predict the pressure drops in the pipes for a range of pipe lengths, diameters and gas pressures for a molecular mixture. The dimensions of the pipes to and from the laser head were selected to optimise the mass flow rate of gas and the differential pressure across the pipes.

The supply pipes to the laser head operate at a pressure in the range 160 to 300 mb. A pressure drop of the order of 10-15 mb is
acceptable since the delivery pressure of the recirculating system can be accommodated by the installed motor power. Volumetric efficiency of the pumps will decrease as a percentage of the total delivery pressure eg 15/300 = 5%. However, the gas return pipes operate at a static pressure of only 40-60 mb. A pressure drop of 10-15 mb at this point of the system would reduce the flow by 15/60 = 25%. The pressure drop must therefore be kept small in this region to maintain the required mass flow rate for laser operation.

The details of the configuration selected of two supply pipes and three return pipes are summarised in Table 7.2.

<table>
<thead>
<tr>
<th>Supply lines - length (m)</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>diameter (mm)</td>
<td>63</td>
</tr>
<tr>
<td>No. of pipes</td>
<td>2</td>
</tr>
<tr>
<td>differential pressure (mb)</td>
<td>9.3</td>
</tr>
<tr>
<td>gas temperature (°C)</td>
<td>&lt;30</td>
</tr>
<tr>
<td>Exhaust lines - length (m)</td>
<td>4</td>
</tr>
<tr>
<td>diameter (mm)</td>
<td>100</td>
</tr>
<tr>
<td>No. of pipes</td>
<td>3</td>
</tr>
<tr>
<td>differential pressure (mb)</td>
<td>3.05</td>
</tr>
<tr>
<td>gas temperature (°C)</td>
<td>&lt;270</td>
</tr>
</tbody>
</table>

Table 7.2 Summary of the flexible gas couplings used.

7.2.3 Gas Injection Flow Paths

The flow path of the recirculating gas through the laser head is represented schematically in Fig 7.3. The "PIPE CONDUCTANCE" program used in Section 7.2.2 was used to select the correct size the
Fig 7.3 Schematic diagram of the gas injection flow paths
components through which the gas was passed. These components included two gas supply elbows, flow manifold block, interconnecting pipes and porous anode feed pipes and nozzles on the high pressure side of the discharge and a water cooled gas manifold and three watercooled gas elbows on the low pressure side of the discharge. The range of sizes and the predicted pressure drops associated with each component are summarised in Table 7.3. All the pressure drops are at a mass flow rate of 0.025 kg/s at an upstream cavity pressure of 50 mb.

<table>
<thead>
<tr>
<th>Component</th>
<th>Sizes and configurations investigated</th>
<th>Size selected (mm)</th>
<th>Pressure drop (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Inlet Elbows</td>
<td>two elbows, (Ø50-100 mm)</td>
<td>Ø69</td>
<td>0.9</td>
</tr>
<tr>
<td>Manifold Blocks/Interconnecting Pipes</td>
<td>four pipes, (Ø25-75 mm)</td>
<td>Ø50</td>
<td>5.4</td>
</tr>
<tr>
<td>Anode Feed Pipes</td>
<td>four to eight pipes, (Ø25-35 mm)</td>
<td>Ø26</td>
<td>17.1</td>
</tr>
<tr>
<td>Anode Nozzles</td>
<td>four to eight nozzles, (Ø10-28 mm)</td>
<td>8xØ19</td>
<td>201</td>
</tr>
<tr>
<td>Gas Exhaust Manifold</td>
<td>three to ten branches, (Ø30-060 mm)</td>
<td>3xØ60</td>
<td>4.0</td>
</tr>
<tr>
<td>Gas Exhaust Elbows</td>
<td>three elbows, (Ø75-150 mm)</td>
<td>Ø100</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 7.3 Summary of component sizes investigated and associated pressure drops.

The two gas inlet elbows were fabricated from stainless steel pipe and fittings and flanged at each end with ISO 63 flanges. The gas then passes through the two Nylatron manifold blocks which supply four 50 mm bore Nylatron pipes. The four pipes feed the manifold
blocks into which the eight 26 mm bore anode pipes are connected and provide the necessary electrical isolation.

The gas was exhausted through a fabricated aluminium manifold which was water-cooled to reduce distortion of the resonator structure from thermal effects. All the components downstream of the discharge were designed to keep the pressure losses small in comparison with the low static pressure of the gas in this region. The component sizes were selected for the rated mass flow of the gas at rated power output of the laser which corresponded to a gas temperature of approximately 240 °C. The gas density at this temperature was approximately 1.7 times that of the cold-flow value with no electric discharge. The gas manifold was designed to provide the necessary mechanical support and rigidity for mounting the gas exhaust elbows and flexible couplings and to transmit this load evenly through the structure of the laser head.

The anodes, which were mounted inside the anode head, provided both the means of conditioning the flow to create the required level of turbulence within the discharge region and also the electrical connection between the discharge and stabilisation circuit. The anode head is shown in Fig 7.4 complete with the aluminium blocks but with the pyrophyllite heat shield removed to expose the electrodes. The anodes were fabricated from 28 mm O/D copper pipe and angled into the discharge tube at 45°. The nozzles were machined from pyrophyllite and the stainless steel mesh fixed inside. Each anode was electrically insulated from the adjacent electrodes with heat shrinkable sleeving placed around the outside surface of the copper pipe and pyrophyllite nozzle. A nozzle diameter of 26 mm was selected to ensure that the rated throughput of the gas recirculating system
could be delivered at pressures below 240 mb. A 48% transmission mesh was used in all the initial tests.

Fig 7.4 Multiple gas injection anode head assembly.

7.2.4 The Laser Head and Optical Resonator

The laser head, connected by a flexible umbilical assembly containing the gas, water and electrical supplies, housed the anode and cathode heads, the optical resonator and discharge tube.

The anode head, described in Section 7.2.3 was mounted on a Tufnol type 10G45 support plate to provide both electrical insulation and mechanical stability. The front mirror assembly was mounted on the opposite side of the plate. The ZnSe front window was held in a water-cooled aluminium mirror mount designed to provide micrometer screw adjustment in two planes and to maintain vacuum tightness between the laser system, atmosphere and cooling water.

The cathode head contained six large surface area water-cooled cathodes. The cathodes were fabricated from 99.5% pure aluminium to
minimise the effects of low work function impurities such as zinc, copper and manganese which increase the tendency of arc root formation on the cathode surface (Section 4.3).

The rear mirror was a water-cooled gold plated copper mirror held in a similar mount to the front window assembly and mechanically held in the resonator box section in a thermally stable Tufnol plate. Both front and rear mirrors are subject to high axial forces due to the atmospheric pressure across their surfaces. The photograph in Fig 7.5 shows the complete laser head assembly with the flexible couplings connected.

7.2.5 Centralised Control and Instrumentation of the Laser

The control and instrumentation equipment was mounted in a standard 19" rack system (Fig 7.6) and a schematic diagram of the complete control and instrumentation system is shown in Fig 7.7. The front panel of the rack was divided into the following functional panels:

- Alarms
- Power control
- Temperature measurement
- Gas instrumentation
- Gas control and blending
- Water cooling control

A microprocessor controlled 28 channel alarm system with annunciator was used to monitor critical operational parameters of the laser system. These parameters included water cooling flows, machine
Fig 7.5 Complete laser head assembly with flexible gas couplings

Fig 7.6 Control and instrumentation rack
Water cooling for optics

Gas recirculation system

Laser head

Power supply

Gas supply system

Fig 7.7 Schematic diagram of control and instrumentation system
temperatures, gas pressures and motor currents. Fig 7.8 shows the
detailed allocation of the alarm system channels. A first-up facility
enabled the primary cause of a fault condition to be indentified
accurately.

A variable gain amplifier was used to increase the full scale
output voltage of the laser power monitor from 100 mV to 2 V to
overcome problems associated with electrical interference from the
electrical machines driving the Roots pumps. The electrical to
optical efficiency of the laser was derived using a multiplier circuit
to measure the electrical power input of the discharge followed by a
divider circuit to divide the laser power signal by the electrical
power signal. A digital instrument was used to display the efficiency
directly on the front panel.

The laser power was controlled remotely by varying the supply
voltage to the high voltage step-up transformer using a motorised
regulating transformer. The main d.c. power supply contactor was also
remotely operated.

Two 12-way electronic thermometers with digital displays were
used to select and display temperatures around the laser system.
Unsheathed chromel-alumel thermocouples were used to measure all the
system temperatures. Special vacuum feed-throughs were designed to
enable thermocouples to be inserted into the vacuum system for
measurement of gas temperatures.
<table>
<thead>
<tr>
<th>WATER FLOW</th>
<th>WATER FLOW</th>
<th>WATER FLOW</th>
<th>WATER FLOW</th>
<th>WATER FLOW</th>
<th>WATER FLOW</th>
<th>WATER FLOW</th>
<th>WATER FLOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>PUMP 1</td>
<td>PUMP 2</td>
<td>PUMP 3</td>
<td>GAS COOLER 1</td>
<td>GAS COOLER 2</td>
<td>GAS COOLER 3</td>
<td>GAS COOLER 4</td>
<td>GAS COOLER 5</td>
</tr>
<tr>
<td>FZAL 1</td>
<td>FZAL 2</td>
<td>FZAL 3</td>
<td>FZAL 4</td>
<td>FZAL 5</td>
<td>FZAL 6</td>
<td>FZAL 7</td>
<td>FZAL 8</td>
</tr>
<tr>
<td>GAS INLET TEMP</td>
<td>GAS INLET TEMP</td>
<td>GAS INLET TEMP</td>
<td>INLET FLANGE TEMP</td>
<td>INLET FLANGE TEMP</td>
<td>INLET FLANGE TEMP</td>
<td>MOTOR CURRENT OVERLOAD</td>
<td>MOTOR CURRENT OVERLOAD</td>
</tr>
<tr>
<td>PUMP 1</td>
<td>PUMP 2</td>
<td>PUMP 3</td>
<td>PUMP 1</td>
<td>PUMP 2</td>
<td>PUMP 3</td>
<td>PUMP 1</td>
<td>PUMP 2</td>
</tr>
<tr>
<td>TZAH 1</td>
<td>TZAH 2</td>
<td>TZAH 3</td>
<td>TAH 1</td>
<td>TAH 2</td>
<td>TAH 3</td>
<td>TAH 1</td>
<td>TAH 2</td>
</tr>
<tr>
<td>MOTOR CURRENT OVERLOAD</td>
<td>WATER FLOW</td>
<td>WATER TEMP</td>
<td>GAS EXIT TEMP (CAVITY)</td>
<td>EARTH LEAKAGE CURRENT</td>
<td>TRANSFORMER TEMP</td>
<td>D.C. OVERLOAD</td>
<td>HELIUM PRESSURE</td>
</tr>
<tr>
<td>PUMP 3</td>
<td>OPTICS</td>
<td>OPTICS</td>
<td>TAH 4</td>
<td>TAH 4</td>
<td>TAH 5</td>
<td>IAH 1</td>
<td>PAL 1</td>
</tr>
<tr>
<td>TZAH 3</td>
<td>FZAL 9</td>
<td>TAH 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NITROGEN PRESSURE</td>
<td>CARBON DIOXIDE PRESSURE</td>
<td>SYSTEM PRESSURE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PAL 2</td>
<td>PAL 3</td>
<td>PAL 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
7.3 DETERMINATION OF THE CLOSED CYCLE LASER PERFORMANCE

7.3.1 Variation of the laser output power over a range of gas flow rates and pressures.

The laser could now be operated continuously, no longer being limited to the 10 s or so of the blow-down system, where many of the laser parameters were changing simultaneously. Continuous operation enabled gas, electric discharge and optical parameters to be varied independently of one another and optimised to increase the laser output power and the electrical to optical efficiency.

The gas flow rate and differential pressure performance of the pumping system is summarised below in Table 7.4. The actual performance was measured by building a heater to simulate the presence of the laser head operating at rated laser output power and flow conditions using 20 2kW mineral insulated heating elements and a variable flap valve to vary the differential pressure across the pumps.

<table>
<thead>
<tr>
<th>Predicted performance</th>
<th>Actual performance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inlet Pressure (mb)</strong></td>
<td><strong>Outlet Pressure (mb)</strong></td>
</tr>
<tr>
<td>40</td>
<td>160</td>
</tr>
<tr>
<td>40</td>
<td>200</td>
</tr>
<tr>
<td>60</td>
<td>210</td>
</tr>
<tr>
<td>60</td>
<td>240</td>
</tr>
</tbody>
</table>

Table 7.4 Summary of the gas flow rate and differential pressure performance of the pumping system.

The new gas injection system described in Section 7.2.3 was fitted into the existing laser resonator used in the blow down system.
in Section 6.4.2 (Fig 7.9). This enabled an assessment to be made of the new gas flow paths and anode head without changing any other parameters such as the resonator structure, cathode head, discharge tube etc. Once the system had been proved to operate satisfactorily within this structure the anode head and gas feed pipes were mounted in the new laser head and tests were carried out to evaluate the operational characteristics of the new system.

Preliminary tests were carried out with the laser using eight gas injection anodes with 26 mm diameter nozzles. The use of these nozzles enabled the full rated flow of the gas recirculating system to be used at the rated differential pressure. A combination of low gas velocity in the anode nozzle and the turbulence generated in the discharge tube limited the maximum stable glow current to less than 1 A. The gas velocity in the anode region was increased by reducing the number of anodes from eight to four and also reducing the diameter of the nozzles. Eight sets of anodes with diameters ranging from 13 to 26 mm were tested to investigate the effect of nozzle diameter on discharge stability. Although the smaller nozzles developed the highest gas velocity the throughput of gas was severely limited to only 0.018 kg/s at the maximum continuous differential pressure of 240 mb available from the recirculating system. As the flow rate decreased the turbulence in the discharge column was also decreased resulting in constriction of the discharge downstream. A compromise between gas flow rate and gas velocity resulted in greatly improved discharge stability with four anodes of 19 mm diameter which enabled continuous stable operation of the discharge at currents of up to 1.7 A at a pressure of 60 mb and a gas flow rate of 0.028 kg/s. The gas velocity at the exit of the anode nozzles was supersonic and estimated
Fig 7.9 Mechanical construction of the laser head mounted in the test facility
to be at least Mach 1.2. This velocity is three times higher than the average entrance velocity of the 93 mm diameter discharge tube when a uniform gas distribution is assumed at a known gas flow rate (i.e., 250 m/s at a gas flow rate of 0.031 kg/s at 50 mb pressure). The interactive effect of these high velocity radial gas jets in the upstream anode region was found to be essential in maintaining the uniformity and stability of the glow discharge at high electrical power loading of the gas (typically 500-700 kW/kg/s) over a pressure range of 30-60 mb.

The gas flow rate and pressures could be varied using the bypass loops incorporated in the gas pumping system (Fig 7.1). A cavity gas pressure of 50 mb was maintained constant and the mass flow rate of gas varied from 0.0162 kg/s to 0.0284 kg/s. The variation of laser output power with discharge current is shown in Fig 7.10. The four curves corresponded to the four different gas flow rates and exhibit the same initial increase of laser power with discharge current demonstrating that the constant cavity gas pressure has a greater influence on the discharge voltage than an increase in gas flow rate. The discharge voltage at maximum laser output was approximately constant at 11.2 kV for the four conditions. The fall off in laser power at discharge currents above 1.2 A was due to both the increase in gas temperature and the formation of streamers within the discharge. The increase in gas temperature to above 270 °C causes a decrease in the gain of the lasing medium because of the thermal population of the lower lasing levels. A rapid decrease in gain is observed as the temperature is raised above this level. Also associated with the rise in temperature and pressure drop along the discharge tube is a significant decrease in the density of the gas. The static pressure
Fig 7.10 Variation of laser output power with discharge current for a range of gas flow rates
ratio and temperature ratio of the gas were calculated using the Rayleigh Line Heating equations which are solved in Appendix 1 and were found to be 0.86 and 1.72 respectively for the highest power conditions. This corresponded to a 2:1 reduction in the average gas density for an electrical power loading of 675 kW/kg/s. There is also a corresponding 2:1 increase in the ratio of electric field to neutral particle density (E/N) for the discharge increasing the probability of streamer formation at the downstream end of the discharge where the gas density is smallest. Over the range of gas flow rates (0.0162 kg/s to 0.0284 kg/s) the electrical to optical efficiency varied from 21% to 25%.

The discharge current at which the formation of streamers started was plotted as a function of gas flow rate in Fig 7.11. A linear dependence of the current was observed over the flow rates investigated. At these high gas flow rates the glow to arc transition instability appears to be a column dominated process rather than electrode dominated. The results of Fig 6.27 in the blow-down system showed a flattening of the curve of current against flow rate at flow rates above 0.005 kg/s. It was suggested that the aerodynamic forces in the column region were beginning to dominate limiting the maximum glow discharge current. The results here at high flow rates support this interpretation and demonstrate the need for turbulent gas flow along the entire length of the discharge tube to maintain column uniformity. It is now possible with the use of these graphs (Fig 7.10 and Fig 7.11) to not only predict the gas flow rate required thermally for a specific laser output power but to also predict the flow rate required to operate the laser at a particular discharge current.
Fig 7.11 Variation of discharge current at which instability occurred with gas flow rate
The gas pressure in the laser cavity was varied over the range 30-60 mb at constant gas flow rate. The lower pressure of 30 mb was selected as being the minimum pressure of interest to operate a high power laser and the upper pressure of 60 mb was limited by the maximum delivery pressure available from the recirculating system with the flow configuration used. The graph in Fig 7.12 shows the variation of electrical power loading of the flowing gas with pressure. The two curves illustrate the rise in power loading for both maximum laser output and maximum electrical to optical efficiency with rising gas pressure. At the higher pressures the density of the gas is higher and there are therefore greater aerodynamic forces acting upon the electric discharge at a given current. The discharge may therefore be operated at higher discharge currents enabling higher electrical power loading of the gas to be maintained. The electrical power loading of the gas corresponding to maximum electrical to optical efficiency was always between 62-65% the value of the loading corresponding to maximum laser power output. The results indicate that substantially higher output powers could be obtained at higher electrical power loadings at gas pressures above 60 mb. The maximum pressure could be increased by increasing the conductance of the gas flow path which would lower the delivery pressure required from the pumping system at higher cavity pressures. Operation of the laser at higher gas pressures is preferable since the pressure losses associated with the flexible gas pipes then represent a lower fraction of the total flow thus enabling either higher gas flow rates to be obtained or alternatively longer flexible pipes to be used at a given gas flow rate.
Fig 7.12 Variation of electrical power loading of gas for maximum laser output power and maximum electrical to optical efficiency.
7.3.2 Operation of the Laser at Maximum Laser Output.

The laser was operated at the maximum gas flow rate (0.031 kg/s) and upstream cavity gas pressure (71 mb) and produced a laser output of 5 kW. The electric discharge current was varied from zero to the maximum stable glow current (1.5 A) over a period of 20 s. The variation of electric discharge power and laser output power with discharge current is shown in Fig 7.13. The discharge voltage remained constant to within 6% over the entire current range yielding a linear rise in discharge power with current. The near constant discharge voltage indicated that the glow discharge was operating in the normal glow regime of the discharge characteristic. This was also confirmed by the observation of the partially covered cathode surfaces with negative glow. The limit on the maximum power developed by the laser was constriction of the discharge column in the downstream region which occurred at a laser power of 5 kW corresponding to a discharge current of 1.5 A. Stable glow discharge currents of up to 1.9 A were sustained for brief periods of time by operating the motors driving the Roots machines at above rated line currents. This enabled the pressure at the outlet of the pumping system to be raised with a corresponding increase in the gas flow rate and hence discharge current. The pressure drop along the discharge tube was found to be 11 mb at the rated gas flow rate and electrical power loading of the gas. This figure compared well with the predicted pressure drop of 10 mb using the equations describing compressible fluid flow with heat addition solved in the Appendix 1.

A summary of the operational parameters of the recirculating laser at 5 kW laser output is given in Table 7.5.
Fig 7.13 Variation of laser output and electric discharge power with discharge current
Table 7.5 Summary of the operational characteristics of the laser at maximum power output.

The laser developed 5 kW of output from an active length of 0.62 m corresponding to a power per unit length of 8.3 kW/m which is higher than any laser reported in the literature. This high power per unit length from a fast axial flow laser dispels the previously reported notion that transverse flow lasers are the configuration required to develop very high output powers from compact lasers (Luxon 1985). The laser output power per mass flow rate 161 kW/kg/s has been increased over the figure of 135 kW/kg/s obtained in the blowdown system (Section 6.4) through optimisation of both discharge and gas parameters. The gas exit temperature of 255 °C shows that the laser medium is being operated near to the thermal limit of 277°C also indicated by the high electrical power loading of the gas (682 kW/kg/s) which corresponds to the maximum predicted power loading for
the inlet Mach number of the gas \((M = 0.33)\). The figures above and the ability to achieve electrical to optical efficiencies in excess of 25\% demonstrate that the technique of gas injection is superior to many of the more elaborate methods (such as EB, rf, SAGE etc) used to excite other high power CO\(_2\) lasers. The maximum laser output from the laser was limited only by the available gas flow.

### 7.3.3 Characteristics of the Output Beam

The spatial characteristics of the output beam were determined with the aid of both a spinning wire beam analyser and Perspex burn patterns in both the near and far field (up to 5 m). The beam analyser enabled oscilloscope waveform measurements to be recorded of the spatial intensity of radiation of the output beam. Fig 7.14 illustrates a typical record of the output beam at a power level of approximately 4 kW for both the X and Y plane of the beam. The output beam profile was uniform and circular having a 'top-hat' profile with random polarisation. The peak to peak variation in intensity was typically 10\% across the beam diameter when the laser cavity was accurately aligned but increased as the mirrors became misaligned. The output beam contained many high order modes characteristic of the high Fresnel number of the long radius cavity configuration (Section 2.7.3).

The beam divergence was measured by taking burn patterns in the near field \((<0.05 \text{ m})\) and the far field \((5 \text{ m})\) and was found to be 8.3 milliradians full angle. The plexiglass burn patterns in Fig 7.15 illustrate the uniformity of the output beam at a power level of 4 kW. The minimum focused spot size obtainable with a 0.3 m focal length
Fig 7.14 Intensity distribution of the laser output beam at a power level of around 4 kW

Fig 7.15 Near and far field Perspex burn patterns of output beam at a power level of around 4 kW
sodium chloride lens was \(8 \times 10^{-3}\) m which makes the beam suitable for cutting applications requiring multikilowatt power levels. The size of the spot is larger than the theoretical spot size of \(7.7 \times 10^{-5}\) m for a 0.3 m focal length lens because of the non-Gaussian distribution of power in the beam and the poor optical quality of the sodium chloride focusing lens.

### 7.3.4 Variable Reflectivity Output Coupler

Although a laser output power of 5 kW has been obtained from the recirculating laser using a 75\% reflective output coupler, it was considered that this reflectivity was not necessarily the optimum value. The following series of tests were carried out to determine the optimum value of output coupler reflectivity to see if any further improvement in laser performance could be expected.

The extraction of energy from the laser cavity at high efficiency is dependent upon the optimisation of the geometry of the cavity, the coupling coefficient, the gas mixture and the electrical power loading of the gas. The gas recirculating system and aerodynamic mixing techniques developed enable high specific power loading of the laser gas (600-700 kW/kg/s) whilst maintaining uniformity of the electric discharge. The dimensions of the laser cavity were selected to utilise the full capacity of the gas recirculating system and to keep the overall size of the laser head as small as possible.

The electrical to optical conversion efficiency of the laser may be written as
\[
\eta_{\text{tot}} = \eta_q \eta_1 \eta_v \eta_{\text{elec}} \eta_{\text{ext}} \tag{7.1}
\]

where \(\eta_q\) = quantum efficiency = 0.41
\(\eta_1\) = 1-(fractional absorption loss through output coupler)
\(\eta_v\) = fractional mode volume available for extraction
\(\eta_{\text{elec}}\) = fractional coupling of electrical energy to the upper laser level
\(\eta_{\text{exp}}\) = fractional output power extraction efficiency

The quantum efficiency of the CO\(_2\) laser is 0.41 and is a function of the relative energy levels of the CO\(_2\) molecule. The value of \(\eta_1\) is near unity for the 10 mm thick zinc selenide output coupler since the absorption loss of the material at 10.6 microns is only 5.6x10\(^{-3}\). The fractional mode volume available for extraction of energy from the lasing medium is dependent upon the geometry of the laser cavity and the curvature of the optics. The value of \(\eta_v\) is unity for a plano-plano cavity where there is no reduction in beam diameter through the active medium. The value of \(\eta_v\) for the plano-concave cavity with a 20 m radius of curvature rear mirror and mirror separation of 0.9 m is estimated to be 0.97. The \(\eta_{\text{ext}}\) term will be shown to be the fraction of available energy extracted per unit volume of the laser cavity and is a function of the cavity losses, the output coupler and the gain length product of the lasing medium. Rigrod (1965) derives an expression for the output radiation intensity obtainable from lasers with homogenous line broadening for the condition that the cavity losses are uniformly concentrated at the resonator mirrors and that the gain coefficient is isotropic and does not change with time.
The equations given by Rigrod relating the output beam intensity to the saturation beam intensity of the lasing medium have been modified to describe the special conditions relating to a cavity with a totally reflecting rear mirror and an output coupler of transmission $t$.

$$I_0 = I_s t \left( g_0 l + \ln(1-a-t)^{1/2} \right) \frac{1}{(a+t)}$$ (7.2)

where $I_0 =$ output beam intensity
$I_s =$ saturation intensity of the medium
$t_s =$ output coupler transmission
$a =$ cavity losses
$g_0 =$ unsaturated gain coefficient of medium
$l =$ length of active region

For a fixed pumping rate there exists an optimum value of the output coupler transmission which maximises the output power from the laser cavity. As the output coupler transmission is increased the power output will also tend to increase because of the greater transmission. The output power would also be expected to decrease under the same conditions since the increased cavity losses through the output coupler would cause the number of photons in the cavity to decrease. The optimum output coupler transmission can be indicated by considering the extraction efficiency - the ratio of the power output at a particular transmission to the maximum power $P_{\text{max}}$ that could be obtained with the resonant cavity considered as a single pass highly saturated amplifier

$$n_{\text{ext}} = \frac{P_0}{P_{\text{max}}}$$ (7.3)

The expression for $P_{\text{max}}$ is obtained by integrating the expression
defining the forward saturation intensity of the length of the cavity \( l \) (Rigrod 1965)

\[
P_{\text{max}} = A I_{\text{max}} = I_s A g \cdot l
\]

where \( A \) = cross sectional area of output beam.

The diffraction losses within the cavity have been calculated for a range of cavity geometries and modes (Fox and Li 1960, Boyd and Gordon 1962). For any particular mode the diffraction loss is a function of the Fresnel number \( N \) only. The losses are always higher for multimode operation than for single low order mode operation due to the smaller mode volume of the latter. The multimode operation utilises a higher proportion of the laser cavity and results in higher output powers. The Fresnel number of the laser cavity was estimated to be 1.42 and the losses to be 2% (Fox and Li 1960, Kogelnik and Li 1966). The loss figure \( a \) represents the power-loss per transit in the laser cavity.

To determine the value of the gain length product of the laser cavity, two zinc selenide output couplers were used with reflectivities of 65% and 75%. By operating the laser under the same conditions of gas flow rate, pressure and electrical power input with each of the two output couplers, it was then possible to solve simultaneously equation 7.2 to find the value of the gain length product and the saturation intensity of the laser cavity. The results of the tests are summarised in Table 7.6.
Table 7.6 Summary of the laser operating conditions for two output coupler reflectivities.

The variation of laser output power with discharge current is shown in Fig 7.16 for the laser operating with output couplers of reflectivity 65% and 75%. All other parameters were held constant throughout the two tests.

Equation 7.2 was rearranged in terms of $I_s$, the saturation intensity and the values of $a$, $t$ and $I_o$ substituted and equated to
Fig 7.16 Variation of laser output power with discharge current for two different output coupler reflectivities.
solve for \( g_0 \). The value of the gain length product was found to be 0.507 which corresponded to an average gain \( g_0 = 0.805 \% / \text{cm} \) for a discharge 0.63 m long. This value of gain compares well with other reported values for lasers operating under similar conditions ranging from 0.5 - 1 \% / \text{cm} (Davis et al 1969). The value of saturation intensity is typical of high power CO\(_2\) lasers operating at 40-60 mb pressure and agrees with theoretical estimates, (Fowler 1971, Svelto 1982).

The values of gain length product and saturation intensity now enable the optimum value of output coupler reflectivity to be found by solving equation 7.2 for a range of reflectivities and identifying the maximum output power. An output power of 5028 W was calculated for the optimum output coupler reflectivity of 89\% and the maximum power \( P_{\text{max}} \) was 6888 W as defined by equation 7.3 with an extraction efficiency of 0.72. The extraction efficiency of the laser with an output coupler reflectivity of 75\% was 0.64. To illustrate the variation of extraction efficiency with output coupler reflectivity equations 7.2 and 7.4 were solved for a range of values of reflectivity and gain length products and is illustrated graphically in Fig 7.17 and Fig 7.18. The curves in Fig 7.17 illustrate the changes in extraction efficiency for a constant loss cavity operating with different gain length products. The broader shape of the curves demonstrate that in high gain lasers the extraction efficiency and hence output power is relatively insensitive to the output coupler reflectivity compared with very low gain lasers. The gain of the laser described here is relatively low \( (g_0 = 0.8\% / \text{cm}) \) which explains the large variation in output power on changing the reflectivity of the output coupler (4398 W @ 75\% R and 3547 W @ 65\%)
Fig 7.17 Variation of laser extraction efficiency with output coupler reflectivity for a range of gain-length products.
Fig 7.18 Variation of laser extraction efficiency with output coupler reflectivity for a range of cavity losses
Although the gain of the laser is relatively low the high value of power output per unit length of the laser (8.3 kW/m) is due to the large cross-sectional area of the cavity, making the product of the output intensity and the cross-sectional area large. The curves in Fig 7.18 show the variation of extraction efficiency with output coupler reflectivity for a constant gain length product with different cavity losses. The peak in extraction efficiency falls rapidly with increasing cavity losses because of the reduced number of photons remaining in the cavity which contribute to laser amplification. An extraction efficiency of 0.64 exists for an output coupler reflectivity of 75% for a cavity of \( a = 0.02 \) corresponding to the operating conditions used to solve the gain equation 7.2.

The value of the gain length product \( g_1 \) was also investigated by using an additional CO\(_2\) laser to probe the discharge under operating conditions and measuring the amplification of the transmitted beam. An 8 W rf excited waveguide laser was used with an output beam diameter of 1.8 mm. The beam was expanded to 17 mm diameter using two zinc selenide lenses mounted on an optical rail and then passed through the laser resonator on the axis of the discharge tube. Sodium chloride blanks were used as transmitting windows and the power measured using a 10 W power monitor. The arrangement is shown schematically in Fig 7.19. The stability of the laser rf waveguide was monitored and its output power-time signature (Waksberg 1971) determined over a period of several hours. Once the probe laser had reached steady state conditions the amplitude stability was better than 1%. The ratio of the amplified signal under conditions of the flowing gas and discharge to the no flow condition gave a direct measurement of the gain of the lasing medium. The gain was found to
Fig 7.19 Schematic diagram of probe laser system for measuring the gain of the high power laser.
vary between 0.4 to 1.08%/cm. The average gain of the laser under operating conditions was found to be 0.71 ie within 15% of the figure determined by the use of variable reflectivity output couplers. The results from the work carried out with the probe laser confirm the validity of the theoretical analysis of the laser cavity and the accuracy of the estimation of the cavity losses (ie a = 0.02).

The optimum value of output coupler reflectivity has been determined (89%) which corresponds to an extraction efficiency of 0.72. Therefore an increase in the output power of the laser would be expected if the output coupler reflectivity was changed from its present value (75%) to the optimum (89%). The increase in extraction efficiency of 12% corresponds to an increased laser output power of 5.6 kW.

7.3.5 High Speed Photography of Discharge Instabilities

A series of tests were carried out to investigate the motion and origin of arc streamers within the glow discharge. A high speed cine camera was used to record the arc streamers over a range of gas flow conditions. The discharge current was adjusted so that both arc streamers and the glow column were present simultaneously without total collapse of the glow column occurring.

The camera was positioned 2 m above the discharge tube with a wide angle lens so that the entire length of the discharge could be viewed through the camera. Framing rates of up to 7200 pps were achieved which corresponded to exposure times of 28 μs. Kodak 200 ASA Tri-X reversal film was used for all the tests. The film required
very slow processing rates to obtain adequate images of the low intensity discharge at high framing rates. A spark gap inside the camera driven by a 1 kHz pulsed power supply enabled reference timing marks to be recorded on the film.

Over the range of discharge currents, gas flow rates and pressures investigated, simultaneous filming of the column and electrode regions confirmed that the arc streamers always developed in the column towards the cathode end of the discharge rather than at the electrodes. Provided adequate surface area is available for conduction at the cathode, the primary cause of arcing in the discharge is collapse of the uniform glow column to a smaller diameter arc discharge. Figure 7.20(a) illustrates such an event starting with collapse of the discharge column without any direct point of attachment of an arc root on an electrode surface. The photographs were recorded at a framing rate of 7100 pps and a gas flow rate of 0.022 kg/s at 50 mb. The gas flow direction is from anode to cathode and is shown next to the photographs. Only the constricted arc is visible on the film at framing rates above 1500 pps because of the relatively high intensity of the arc compared with the glow discharge. No propagation of the arc was observed in a direction counter to the gas flow. This is contrary to the mechanism proposed by Carlson (1976) who suggested that the arc propagates from the cathodes upstream towards the anodes in a direction opposed to the gas flow. No photographic investigations were made by Carlson. The arc appears to be swept out of the discharge region in a time similar to the dwell time of the flowing gas which is consistent with the observations and predictions of Nighan (1973).
Fig 7.20 High speed cine photographs recording movement of arc instabilities within the glow discharge column

(a) $m = 0.022 \text{ kg/s, 7100 pps}$

(b) $m = 0.011 \text{ kg/s, 7100 pps}$
The photographic record shows that there are two distinct axial velocities associated with the movement of the arc in the discharge tube. The velocities correspond to each end of the arc within the flowing gas. The velocities were determined by measuring the displacement of the image of the arc along the discharge tube. The upstream end of the arc had a velocity similar to the velocity of the flowing gas. This velocity was measured over a range of flow rates and was found to vary from 213 m/s at a flow rate of 0.0112 kg/s to 307 m/s at a flow rate of 0.022 kg/s. The corresponding average gas velocities at these flow rates were 173 m/s and 339 m/s. The velocity associated with the downstream end of the arc was constant over the range of flows investigated and was found to be 480 m/s, considerably faster than the average gas velocity. This could be explained by the higher temperature of the gas on the downstream side of the constriction which would reduce the growth time of the instability (Nighan and Weigand 1974). The two sequences of photographs in Fig 7.20(a) and (b) illustrate the effects of changing the gas flow rate. The flow rate in Fig 7.20(a) is twice that of Fig 7.20(b) and the difference in velocities associated with the upstream end of the arc can be clearly seen.

A periodic sequence of arc initiation and extinction was observed under all the conditions of gas flow rates investigated. The frequency of this sequence of events was estimated to be 300 Hz which corresponded to the frequency of the power supply ripples. The variation of supply voltage was approximately 800 volts peak to peak which corresponded to a 5% change in the value of \( E/N \) of the discharge. The increase in \( E/N \) was sufficient to cause arcing.
Although most of the events recorded photographically occurred in the region between the mid-point of the tube and the cathodes, a number of events occurred immediately upstream of the cathode. No evidence was found to suggest that the mechanism for these arcs was different to the one suggested for the positive column instabilities. The intensity of the gas turbulence generally decreases as the gas flows from the anode region to the cathode region. The arcs were therefore likely to occur toward the cathodes because of the lower intensity of gas turbulence and because of the increased gas temperature which lowers the gas density and hence raises the $E/N$ of the discharge increasing the possibility of arcing.

The region just upstream of the cathodes has a higher current density associated with it because of the change in direction of the transition region between the fully developed column and the submerged cathodes. The effect of this is reduced to some extent by the change in cross-section of the gas path at the end of the discharge tube which increases the gas turbulence immediately in front of the cathodes. This turbulence improves the heat transfer from the cathode surface and thus reduces the tendency of arcs to develop. The photographic observations illustrate the importance of turbulent gas flow along the entire length of the discharge tube.
7.4 SUMMARY OF RESULTS

A compact laser head less than 1.1 m long has been produced using separately stabilised multiple electrodes and gas injection anodes which develops a continuous laser output power of 5 kW at an electrical to optical efficiency of 24% from a single discharge tube 600 mm long and 93 mm dia. The specific laser output power of 8.3 kW/m of discharge is three times greater than any other gas recirculating laser reported in the literature.

The laser performance has been investigated over a range of gas flow rates and pressures and is able to operate stably near the thermal limit of the gas flow indicating the effectiveness of the multiple electrode and gas injection techniques used.

The output beam has been studied and the beam profile, beam divergence and mode structure determined over a range of laser output powers. The gain of the lasing medium was determined independently using both an analytical method and a probe laser and the optimum value of the output coupler reflectivity determined.

A high speed photographic study of arc streamer formation and propagation within the glow discharge was carried out over a range of flow conditions. Two distinct velocities of propagation were identified for the ends of the streamers which formed in the glow discharge and an explanation for their presence suggested.
8.1 CONCLUSIONS

The interaction of turbulent gas flows with multiple glow discharges has been investigated and the results applied to developing a compact 5 kW fast axial flow CO₂ laser. The problems of instability and constriction of the glow discharge common to many high power CO₂ lasers have been dramatically reduced using a combination of separately stabilised multiple electrodes and gas injection anodes. The maximum glow discharge current typical of conventional fast axial flow CO₂ lasers has been raised from 0.15-0.2 A to around 2 A, representing a 7-10 fold increase in discharge current. The increase in discharge current has enabled a laser output power of 5 kW to be developed from a discharge only 600 mm long, equivalent to a specific laser output power per unit length of discharge of 8.3 kW/m compared with conventional CO₂ lasers (including rf excited) which typically develop a laser output power of 0.5-2.5 kW/m of discharge.

The behaviour of multiple glow discharges has been studied over a wide range of electrode geometries, electrical configurations, gas flow fields, pressures and flow rates. Techniques have been developed which enable discharge powers in excess of 25 kW to be achieved whilst maintaining the stability and uniformity of the multiple glow discharges at diameters of up to 134 mm with electrode separations of up to 1000 mm. The advantages of using separately stabilised multiple electrodes with large surface area cathodes have been demonstrated and shown to be important in raising the current at which the glow to arc transition occurs.
The interaction of glow discharges with an external magnetic field to produce rapid rotation of the discharge has been investigated and shown to be an effective method of uniformly distributing glow discharges at high powers. The maximum electrical power input to the discharge was raised by a factor of six by using an axial magnetic field of up to 0.5 T to rotate a glow discharge in a coaxial electrode arrangement at rotational frequencies of up to 2 kHz. Uniform glow discharges have been produced which could be used for the excitation of a high power CO$_2$ laser.

The effects of gas turbulence on various regions of the glow discharge have been investigated and the conditions at the anode fall region identified as being very important in determining the physical characteristics of the glow discharge. A series of tests was carried out to establish the parameters associated with the design of the anode and associated gas flow which affected the behaviour of the multiple glow discharge system. The resulting gas injection anode ensures intimate coupling of the turbulent gas flow with the anode fall region and has enabled the operation of glow discharges which remain stable and spatially uniform at previously unattainable power levels.
8.2 RECOMMENDATIONS FOR FURTHER WORK

(1) Development of a gas flow visualisation system to study the transonic gas flow in the gas injection anodes and in the column region of the discharge. Two techniques which could be applied include the use of either a pulsed ruby or CW frequency-doubled YAG based holographic interferometer or the use of electronic speckle pattern interferometry (ESPI).

(2) Investigate the effects of using a profiled supersonic anode nozzle to increase the entrance velocity of the gas into the laser cavity and to reduce the pressure drop across the anodes which would reduce the complexity of the gas recirculating system.

(3) Investigate the various methods of obtaining single low order mode output from the laser, including the positive branch confocal unstable resonator and the multiple pass stable resonator.

(4) Investigate the frequency spectrum of the turbulence generated by the gas injection anodes to confirm the importance of microturbulence in stabilising the discharge. This could be done using a piezo-electric pressure transducer via a probe into the discharge coupled to a spectrum analyser.

(5) Study the operational characteristics of the 134 mm dia multiple discharge developed at higher gas flow rates (>0.04 kg/s) to extend the range of the laser output power into the 20 kW region.
(6) Determine the long term suitability of the 5 kW laser to materials processing applications including the cutting, welding, heat-treatment and surface cladding of metals and ceramics using appropriate beam handling equipment and a power supply that would enable the laser to be pulsed.

(7) Investigate the possibility of applying the multiple discharge and gas injection anode techniques to other commercially available high power CO₂ lasers to raise the laser output power and improve the operating characteristics of these lasers.

(8) Investigate the application of the large volume high power glow discharge to low pressure chemical synthesis of gaseous compounds.
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APPENDIX 1

DERIVATION AND SOLUTION OF THE COMPRESSIBLE FLUID FLOW EQUATIONS FOR A LASER CAVITY WITH HEAT ADDITION

Consider the continuity equation

\[ g \rho_1 V_1 = g \rho_2 V_2 = \frac{\dot{m}}{A} = \text{const} \quad (1) \]

where subscripts refer to location
- \( g \) = acceleration due to gravity
- \( \dot{m} \) = mass flow rate
- \( \rho \) = gas density
- \( A \) = area of duct
- \( V \) = gas velocity

In the absence of friction (i.e., friction losses are assumed to be negligibly small compared with the effect of the heat addition), conservation of momentum requires

\[ P_1 A + \rho_1 A V_1^2 = P_2 A + \rho_2 A V_2^2 \quad (2) \]

where \( P \) = static gas pressure

Combining equations (1) and (2)

\[ P_1 - P_2 = \frac{\dot{m}}{A g} (V_2 - V_1) \quad (3) \]

For a perfect gas

\[ \rho V^2 = \gamma P M^2 \quad (4) \]
where \( \gamma = \) ratio of specific heats at constant pressure and control volume

\[ M = \text{Mach number} \]

The static pressure change can then be defined by

\[
\frac{P_2}{P_1} = \frac{1 + \gamma M_1^2}{1 + \gamma M_2^2}
\]

By the perfect gas law

\[
\frac{P_2}{P_1} = \frac{P_2 T_2}{P_1 T_1}
\]

Combining equations (4), (5) and (6)

\[
\frac{T_2}{T_1} = \left[ \frac{M_2(1 + \gamma M_1^2)}{M_1(1 + \gamma M_2^2)} \right]^2
\]

and the density ratio follows

\[
\frac{\rho_2}{\rho_1} = \frac{M_1^2(1 + \gamma M_2^2)}{M_2^2(1 + \gamma M_1^2)}
\]

All the changes in fluid properties are established in terms of changes in the Mach number but without reference to the heat transferred to the gas between locations 1 and 2. A key relationship is thus required to associate the heat transfer to the change in Mach number. This is obtained in terms of the stagnation temperatures from the first law of thermodynamics.
\[
Q = h_2 - h_1 + \frac{v_2^2 - v_1^2}{2g} = h_{g2} - h_{g1}
\]

\[
= c_p(T_2 - T_1) + \frac{v_2^2 - v_1^2}{2g} = c_p(T_{g2} - T_{g1})
\]

where \( h \) = enthalpy of gas
\( Q \) = energy transfer

\[
Q = \frac{T_{g2} - T_{g1}}{c_p}
\]

\[
\frac{Q}{T_{g1}c_p} = \frac{T_{g2} - T_{g1}}{T_{g1}}
\]

\[
Q = \frac{\dot{m}Q_T}{\dot{m}}
\]

where \( Q_T \) = total energy transfer

\[
\frac{T_{g2}}{T_{g1}} = 1 + \frac{Q_T}{\dot{m}c_pT_{g1}}
\]

(9)

thus, ignoring all other flow, the electrical input to the gas will change the stagnation temperature of the fluid.

The use of these Rayleigh line equations as derived is difficult because of the complex functions involving the Mach numbers. It is therefore more convenient to normalise the equations by referencing
the conditions that exist where \( M=1 \), which is constant for any particular flow condition. Location 1 is chosen as the point where \( M=1 \), the various parameters are denoted by an asterisk \((*)\) at that location. The downstream pipe location becomes any location in general and the subscript 2 is deleted.

The equations can be written more simply

\[
\frac{P}{P^*} = \gamma + 1 \frac{1}{1 + \gamma M^2} \tag{10}
\]

\[
\frac{T}{T^*} = \left[ \frac{(1 + \gamma M)}{1 + \gamma M^2} \right]^2 \tag{11}
\]

\[
\frac{V}{V^*} = \frac{\rho}{\rho^*} = \frac{(\gamma + 1)M^2}{1 + \gamma M^2} \tag{12}
\]

The stagnation pressure ratio is obtained from

\[
\frac{P_{02}}{P_{01}} = \left[ \frac{1 + \gamma M_1^2}{1 + \gamma M_2^2} \right] \left[ \frac{1 + \left( \frac{\gamma - 1}{2} \right) M_2^2}{1 + \left( \frac{\gamma - 1}{2} \right) M_1^2} \right] \frac{\gamma}{\gamma - 1}
\]

Hence

\[
\frac{P_0}{P_0^*} = \left( \frac{\gamma + 1}{1 + \gamma M^2} \right) \left[ \frac{2 (\gamma - 1) M^2}{(\gamma + 1)} \right] \frac{\gamma}{\gamma - 1} \tag{13}
\]

Similarly, the temperature ratio...
Expanding equations (14) and rearranging into the general quadratic form

\[
M_2^4 \left[ \frac{\gamma^2}{T_0} - (\gamma+1)(\gamma-1) \right] + M^2 \left[ \frac{2\gamma T_0}{T_0^*} - 2(\gamma+1) \right] + \left[ \frac{T_0}{T_0^*} \right]^2 = 0 \quad (15)
\]

Solving equation (15) to find \( M^2 \), the downstream Mach number

\[
M_2^2 = \frac{\left[ 2\gamma \left[ \frac{T_0}{T_0^*} \right] - 2(\gamma+1) \right] \pm \sqrt{2\gamma \left[ \frac{T_0}{T_0^*} \right] - 2(\gamma+1)^2 - 4 \gamma^2 \frac{T_0}{T_0^*} - (\gamma+1)(\gamma-1) \left[ \frac{T_0}{T_0^*} \right]^2}}{2 \gamma \left[ \frac{T_0}{T_0^*} \right] - (\gamma+1)(\gamma-1)} \quad (16)
\]

Since both the upstream and downstream Mach numbers are now both known, the temperature and pressure ratios of sonic to static conditions can be determined for the inlet and outlet conditions.
\[
\begin{bmatrix}
T \\
T^*
\end{bmatrix}_1 = \frac{(\gamma+1)M_1^2}{1 + \gamma M_1^2} \quad (17)
\]

\[
\begin{bmatrix}
P \\
P^*
\end{bmatrix}_1 = \frac{\gamma+1}{1 + \gamma M_1^2} \quad (18)
\]

From equations (17) and (18) the static temperature and pressure ratios can now be solved for the inlet and outlet conditions.

\[
P_2 = \frac{P}{P^*_2}
\]

\[
P_1 = \begin{bmatrix}
P \\
P^*
\end{bmatrix}_1 \quad (19)
\]

\[
T_2 = \frac{T}{T^*_2}
\]

\[
T_1 = \begin{bmatrix}
T \\
T^*
\end{bmatrix}_1 \quad (20)
\]

The absolute values of the outlet flow conditions are now obtainable knowing the inlet gas pressure, entrance Mach number and electrical power input to the flowing gas.
APPENDIX 2

COMPUTER DATA ACQUISITION PROGRAMS

***** OVRDLG *****

10 LDHEN=2200F:FX7,8
20 *FX8,8
30 *FX11,0
40 OENERGORDT60
50 DING(10,5),SR(10),CH(10),FS(10),UN(10),BN(10),SC(10),N(10):FORI=1TO10:SB(I,1)=1:NEXT
60 RT=0:HR=0:HN=0:SC=0
70 CLOSE0:MODE7
80 *FX5,4
90 *FX2,0
100 PRINTTAB(3,4)**"LASERLOG**".TAB(1,6)**"Menu-".TAB(0,8)**"Set Time" - T**"PRINT".Recall

Table - R**"PRINT".Edit Group Table - G**"PRINT".Set Up SPECTRA - S**"PRINT".Look from SPECTRA -
L**"PRINT".Data from Disk - D**"PRINT".
110 PRINT**"Clear Group Table" - C**"PRINT".Keep Group Table - K**"PRINT".Examine Results - E**

120 IFRT=1THEN140
130 PROCSTTIM.E=220005:PRINTTAB(0,19)**"Time" **"HR/HN/SC
140 INPUTTAB(3,20)**"Option "**A=IFA#**"T"**THEN80
150 PROCCLRLLN:IFA#="T"THEN680
160 IFD=**"0"THEN250
170 IFD="T"THENL.SBGR 15FF
180 IFD="L" THENL.LBRIP 15FF
190 IFD="B" THENL.DCIP 15FF
200 IFD="C" THENL650
210 IFD="E" THENCHAIN**"TABULAR"**
220 IFD"A"ANDA<**"K" THENBGT0950
230 GSBSUB160
240 CLOSEC&:GTD060
250 PROCCLRTORP
260 PRINTTAB(1,20)**"Alter Group Table" - I**"PRINT".Add D-delete C-change E-exit **";INP UTA=#**"A"**"THEN80
270 IFD="D"THEN820
280 IFD="C" THEN310
290 IFD="E" THEN420
300 BGT060
310 PROCCLRLIN
320 PRINTTAB(1,15)**"INPUT".Group Number to Change - E**"PRINT".Lo Chan - S**SB(8,1)**"INPUT"&**IFLEN(A8)**"OTHENS(8,11)=VAL(A8)
330 PRINT**"Hi Chan - **SB(8,2)**"INPUT"&**IFLEN(A8) **"OTHENS(8,2)=VAL(A8)
340 PRINT**"Units - **SB(8,3)**"INPUT"&**IFLEN(A8)**"OTHENS(8,3)=VAL(A8)
350 PRINT**"Scale - **SB(8,4)**"INPUT"&**IFLEN(A8)**"OTHENS(8,4)=VAL(A8)
360 PRINT**"Intg cd - **SB(8,5)**"INPUT"&**IFLEN(A8)**"OTHENS(8,5)=VAL(A8)
370 BGT0250
380 PROCCLRLIN
390 PRINTTAB(1,15)
400 INPUT**"Group no. (1-10) "**SB(8,1)**"INPUT".Low chan (0-31) "**L1**"INPUT".Hi chan (0-31) "**H1**"INPUT".Units (0-15) **".U="**INPUT**"Scale (0-9) "**.S**"INPUT**"Intgr cod (1-12) **".I**"INPUT**"(8,1)=LSB(8,2)=MSB(8,3)=USB(8,4)=LSB(8,5)=16BTO250
410 SBSB(8,2)=MSB(8,3)=USB(8,4)=LSB(8,5)=16BTO250
420 FORB=1TO10:IFB=16B(8,13)**"OTHENS470
430 FORCHR=1TO16:IFCHR=16B(8,13) **"OTHENS470
440 PRINT**"Please enter name of parameter measured on channel "**CHR**"VDU9**"INPUT"**CH**"VDU1
450 PRINT**"What would be its value at full scale "**INPUT**"(CHI)"**VDU10
460 INPUT**"What are its units "**UN**"(CHI)"**NEXT
470 NEXT
480 NBSB=**"X"**FORD=1TO10:IFB=16B(8,13) **"OTHENS500
490 NBS=**"X"**FORD=1TO10:IFB=16B(8,13) **"OTHENS500
500 NEXT
510 BGT060
520 PROCCLRLLIN
530 PRINTTAB(0,15)**"INPUT".Group number to Delete **SB(8,1)=**16BTO250
540 DEF PROCCLRTORP
550 CLSB**"PRINT"**PRINT**" GROUP CHANS UNITS SCALE INT"**PRINT **" LO HI **"PRINT** "
560 220005:FORG=1TO10:IFS(B(1,1))**"OTHENS570
570 PRINT**"SB(1,1),SB(1,2),SB(1,3),SB(1,4),SB(1,5)
580 NEXT
590 ENDPROC
590 DEF PROCCLRLLIN
600 FORIS=20TO24:PRINTTAB(1,13)***GOSUB630
610 NEXT
620 ENDPROC
630 FORI=0 TO 35: PRINT " *" : NEXT
640 RETURN
650 PRINTTAB(0.21): "Clear group table" : INPUT "Are you sure (Y/N) " : A$: IF A$="Y" THEN 60
660 FOR I=0 TO 30: S$(I,1) = "NEXT: GOT0 60
670 GOTO 60
680 PRINTTAB(0.21): INPUT "Hour " : H$: HR$=H$+3600: MN$=M$: AT$=TIME: GOTO 60
690 DEF PROD TIST
700 TNDW=HR$=INT((TIME-AT$)/100): HR$=INT((TNDW+3600)/60): SC=TNDW-HR$-3600: MN=$
60: IF HR$>=23 THEN HR$=24
710 ENDPROC
720 "FX3.4
730 IF DEV$="F" THEN CLOSE $8
740 PRINT "NEXT"
750 "FX3.4
760 PRINT "NEXT"
770 RETURN
780 REM PADDIN8 ZZZZZZZ
790 DEFERROR GOTO 870
800 INPUT "Channel to be plotted on the horizontal axis " HX$:INPUT "Channel to be plotted on the left vertical axis " LV$:INPUT "Channel to be plotted on the right vertical axis " RV$: HS=FB(HX)/10 : LV$=FB(LV)/10
810 RV$=FB(RV$)/10: MODE$="O120109
820 PLOT4.200,252=PLOT5.302,120,0=PLOT1.120.252,200,220=PLOT5.120,252,200=PLOT5.1100,932
830 PRINTCHR$(13)+"TAB$(0)*" : CH$(RV$): PRINTTAB(5)UN$(LV$): TAB$(65)UN$(RV$): PRINTTAB(5.26)
840 FOR R=1=1 TO 8: PRINTTAB(0.27): "Save screen to printer - P" : IF X$="FX2.0
850 PRINT " or restart - R" : IF X$="FX3.0
860 PRINTTAB(225): "option +1:VDU9,127:SAVEAS IF$AV$="P" THEN 920
870 IF$BAV$="R" THEN 860
880 PRINT "DI8K DATA"
890 PRINTTAB(5): "to Display "
900 PRINTTAB(5): "Graph "
910 PRINTTAB(5): "File name "
920 INPUTTAB(22,24): "Option *:DEV$"
930 PROCCLR LIN
940 IF DEV$="D" THEN 1020
950 IF DEV$="G" THEN 1040
960 ML TAB 1276
970 G:ML = 1276
980 IF EO$FB THEN 1190
990 IF EOF$FB THEN 1190
1000 IF EOF$FB THEN 1190
1010 IF EOF$FB THEN 1190
1020 ML TAB 1276
1030 IF EOF$FB THEN 1190
1040 IF EOF$FB THEN 1190
1050 IF EOF$FB THEN 1190
1060 IF EOF$FB THEN 1190
1070 IF EOF$FB THEN 1190
1080 IF EOF$FB THEN 1190
1090 IF EOF$FB THEN 1190
1100 IF EOF$FB THEN 1190
1110 IF EOF$FB THEN 1190
1120 IF EOF$FB THEN 1190
1130 IF EOF$FB THEN 1190
1140 IF EOF$FB THEN 1190
1150 IF EOF$FB THEN 1190
1160 IF EOF$FB THEN 1190
1170 IF EOF$FB THEN 1190
1180 IF EOF$FB THEN 1190
1190 IF EOF$FB THEN 1190
***** SULGR *****

3000 \*FX3.7
3010 \*FX2.1
3015 \*FX15.0
3020 PRINT\*1,FORI=10TO2000:NEXT\*I:PRINT\*E0.5:PRINT\*D:INPUT\#1:FORI=1TO10:IFSB(1,1)<THEN3190
3090 \*FX3.5
3100 PRINT\*8.1,SB(1,1),SB(1,2),SB(1,3),SB(1,4),0,SB(1,5)
3101 FOR\*X=1TO10:NEXT
3102 INPUT\#1:FX3,4
3130 IFLEFT\#(R,1)="!"THEN3190
3140 PRINT\*SET-UP FAILURE\*PRINT\*CHECK GROUP SETTINGS\*PRINT\*HIT RETURN TO CONTINUE\*\*FX2.0
3180 INPUT\#1:GT03140
3190 NEXT!
3200 \*FX3.0
3210 \*FX2.0
3211 \*E10
3215 FOR\*X=1TO50:BRX=BRX(SQR(X)):FORCX=SB(BRX,1)TOSB(BRX,2):SC(CX)=1:NEXT(SC(2))=6.74:SC(3)=60125:B
C(4)=40:SC(5)=100
3220 INPUT\*DO YOU WISH TO CALIBRATE THE SYSTEM, Y/N\*:IF\#="Y"THEN3373
3224 IF\#="N"THEN3260
3250 BDTO3220
3250 BDTO140
3373 INPUT\*FOR HOW MANY CHANNELS DO YOU WISH TO TYPE IN CORRECTION FACTORS\*:IZ\*IF\#="Y"THEN3380
3374 FOR\*X=1TOIZ:INPUT\*CHANNEL \*C\*:PRINT\#C(CH\#):INPUT\*CORRECTION FACTOR\*:SC(CX)\*NEXT
3380 MODE7
3390 BDTO3140

***** DSCIP *****

3000 PRINT TAB(5,21):"DISK DATA-" D*
3010 PRINT TAB(5):"to Display" B*
3020 PRINTTAB(5):"Graph" B*
3030 INPUTTAB(22,24):"Option \*1DEV\#"
3035 PROCCLRBLN
3040 IF \#="D"THEN3060
3050 IF \#="E"THEN3075
3060 \*L. TABL 1276
3070 \*L. BPRH 1276
3076 \*L.600=8&B:BDTO3080
3075 \*L. BPRH 1276
3080 INPUTTAB(5,21):"Filename \*1D$\#:F$\#:1.8. \#D$
3090 IF\#="R"THEN RETURN
3120 INPUT\#1.X:MCX:FORX110.NX\#INPUTC\#X,BRX\#6X\#(Q\#)=BRX1FORX110\#6X\#INPUTC\#X,BRX\#CX\#1:NEX
T:FORCH=SB(BRX,1)TO SB(BRX,2):INPUTC\#X,CH\#(CH\#),FS(\#CH\#),UN\#(CH\#),SC(\#CH\#)\#NEXT:NEXT
3121 IF\#="R"THEN RETURN
3128 \*E10
3129 \*FX3.0
3130 BDUB2700
3140 INPUT\#1.X:MH\#DMC\#:FORX=1TO7:BRX=BRX(SQR(X)):FORP\#=SB(BRX,1)TOSB(BRX,2):INPUTC\#X,S\#P\#\#N
(P\#)=S\#P\#(S\#P\#)\#SC(\#P\#)/(S\#P\#)\#NEXT:NEXT
3150 BDUB2830
3160 IFDOFECK THEN 3180
3170 BDTO3140
3180 CLOSEC\#
3190 BDUB27900

***** GRPH *****

2700 ONERRB0GT02900
2710 INPUT\*Channel to be plotted on the horizontal axis \*HX\#INPUT\*Channel to be plotted on the left vertical axis \*LVX\#INPUT\*Channel to be plotted on the right vertical axis \*RVX\#H\#F\#(H\#)/10 \#LVX\#F\#(LVX)/10
2720 RVX=F\#(RVX)/10:MODE0;\#420109
2730 PLOT4,200,252;PLOT5,200,932;PLOT4,200,252;PLOT5,1100,252;PLOT5,1100,932
2770 PRINTCH\#1.V= **1TAB(60)*Y \* (CH\#(RVX))PRINTTAB(5)UN\#(LVX)TAB(65)UN\#(RVX)PRINTTAB(50,26)
3000 CH\#H;="\#5UN\#(HZ);VUD5
2790 FOR\#2=90TOB0STEP90;PLOT4,200+OZ,240;PLOT1,0,20;PLOT4,80+OZ,232;PRINT\#S;QZ/90;NEXT;FOR\#2=6
B700GOTO40;PLOT4,10,265+OZ;PRINTLV5\#Z/68;PLOT4,190,252+OZ;PLOT1,20,0;PLOT4,1090,252+Q;PLOT1
20,0;PLOT4,1066,260+OZ;PRINTRV5\#Z/68;NEXT;VUD5
2820 RETURN
2733 MOVE0.1023:PRINT"Channel Full Scale Channel Full Scale"


2735 CRX=CRX+1:EXIT:GOTO2737

2736 CCX=CRX:EXIT:GOTO2735


2738 VDU4:CLS

2739 $=10

2740 RETURN

2763 ONEERROR GOTO2900


2766 $=10

2767 RETURN

2780 CLOSEO:GOTO2

2901 $=FX.0

2902 PRINT:PRINT:PRINT"PRESS ANY KEY TO RETURN TO MENU"

2905 $=GET$.

2910 GOTO140

***** LGRIP *****
10 \#FX3,0
30 MODE$3
40 DIM (\$3(3,3),BR(3),CH\$1(11),FS(11),UN(11),BNX(3),BC(5),N(11)
50 D=0:0=0:F=0:8=0:H=0:J=0:K=W=0:M=0:N=F=0:B=0
60 \#MA28.81AM=1.78:HCPS=0.00001667;CSA=.006938
70 volts_max=26
80 dia_samps_max=7
85 elec_power_max=100000
90 laser_power_max=6013
100 pressure_max=81
110 vol_flow_max=7
120 efficiency_max=31
130 temp_max=1300
140 power_load_max=2000
150 gas_vel_max=1000
151 CoverH_max=10000
152 CoverP_max=50
160 MODE$3
170 CLOSE$0
180 PRINTTAB(7,13)"1 - TABLES (A) AND (B) ON SCREEN",TAB(7,15)"2 - HEADER ON PRINTER",TAB(7,17)"3 - TABLE (A) ON PRINTER",TAB(7,19)"4 - TABLE (B) ON PRINTER",TAB(7,21)"5 - GRAPH",TAB(7,23)"6 - NEW PARAMETERS"
190 PRINTTAB(7,27)"PRESS A NUMBER - "t1:88=GET$<CLS)
191 IFVAL(88)<1 OR VAL(88)>6 THEN 180
195 \#FX21,0
200 IF\$="5"THEN590
210 PRINTTAB(7,31)"PRESS P IF DATA HAS BEEN PROCESSED, R IF RECORDED BY LOGGER"t1:88=GET$<CLS)
214 IF H=$("P" AND H=$("R" AND H=$("p" AND H=$("r")
217 \#FX21,0
220 INPUTTAB(7;3)"DATA-FILE NAME="t1:88=GET$<CLS)
230 IF\$="1" AND H=$("P"THEN CLS
240 IF\$="P"THEN320
250 IF\$="R"THEN270
260 SOT0200
270 INPUTTAB(7,5)"BASING INTERVAL"TAB(32)"INTEGER INPUT TAB(7,7)"BAS SUPPLY PRESSURE (p.s.i.a.)
280 \#="60005 $PRINTTAB(7,11)"MASS FLOW RATE kg/s)"t1:88=GET$<CLS)
290 INPUTTAB(7,13)"DATE AND TIME OF TEST"t1:88=GET$<CLS)
300 INPUTTAB(7,15)"COMMENTS:"t1:88=GET$<CLS)
310 H1=OPENOUT(HE1:"PRINTEX.integ$,supply,flow,mass_flow,datet,co$CLOSE$H1<CLS)
320 IF\$="1"THEN PROCtable
330 IF\$="2"THEN PROCheader
340 IF\$="3"THEN PROCprintA
350 IF\$="4"THEN PROCprintB
360 IF\$="5"THEN B0T0160
370 MODE$3:B0T0180
380 END
390 DEF PROC$integ
400 IF H=$="P" THEN RX=OPENIN R$
410 IF H=$="P" THEN 430
420 C=OPENIN F$
430 IF H=$="P" THEN INPUT\$\$=GET$<CLS)
450 PRINTEX\$\$=GET$<CLS)
460 ENDPROC

### TABULAR ###

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<td>Gas_vel_max</td>
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<td>CoverH_max</td>
<td>10000</td>
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<tr>
<td>CoverP_max</td>
<td>50</td>
</tr>
</tbody>
</table>

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285
470 DEF PROCdata
480 IF#<>"P" THEN 500
490 INPUT X, Y, Z; FOR X=1 TO 1000; FOR Y=1 TO 1000; FOR Z=1 TO 1000;
500 INPUT X, Y, Z; FOR X=1 TO 1000; FOR Y=1 TO 1000; FOR Z=1 TO 1000;
510 IF#<>"P" THEN 500
520 INPUT X, Y, Z; FOR X=1 TO 1000; FOR Y=1 TO 1000; FOR Z=1 TO 1000;
530 IF#<>"P" THEN 500
540 INPUT X, Y, Z; FOR X=1 TO 1000; FOR Y=1 TO 1000; FOR Z=1 TO 1000;
550 IF#<>"P" THEN 500
560 INPUT X, Y, Z; FOR X=1 TO 1000; FOR Y=1 TO 1000; FOR Z=1 TO 1000;
570 IF#<>"P" THEN 500
580 IF#<>"P" THEN 500
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1100 IF#<>"P" THEN 500
1110 IF#<>"P" THEN 500
1120 IF#<>"P" THEN 500
1130 IF#<>"P" THEN 500
1140 IF#<>"P" THEN 500
1150 IF#<>"P" THEN 500
1160 IF#<>"P" THEN 500
1170 IF#<>"P" THEN 500
1180 IF#<>"P" THEN 500
1190 IF temp<0 OR temp>temp_max THEN PRINTTAB(33)"*";"1:GOT01210
1200 IF 4<temp<PRINTTAB(31)"*";1:GOT01230
1210 IF power_load<0 OR power_load>power_load_max THEN PRINTTAB(42)"*";1:GOT01230
1220 IF 4<power_load<PRINTTAB(40)"*";1:GOT01230
1230 IF gas_vel<0 OR gas_vel>gas_vel_max THEN PRINTTAB(51)"*";1:GOT01250
1240 IF 4<gas_vel<PRINTTAB(49)"*";1:GOT01250
1250 IF EoverN<0 OR EoverN>EoverN_max THEN PRINTTAB(60)"*";1:GOT01270
1260 IF EoverP=31201041PRINTTAB(60)EoverN
1270 IF EoverP=0 OR EoverP>EoverP_max THEN PRINTTAB(73)"*";1:GOT01290
1280 IF=K=201041PRINTTAB(71)EoverP
1290 ENDPROC
1300 DEF PROCprint$;CLS;VDU2,1,27,1,71:PROCTable:VDU1,27,1,80,3:ENDPROC
1310 DEF PROCprint$;CLS;VDU2,1,27,1,71:PROCTable:VDU1,27,1,80,3:ENDPROC
1320 DEF PROCresults displaced uses first #:PRINT$2,mas_flow:ENDPROC
1330 IF DIS=PRINTTAB(32)"*";1:GOT01250
1340 IF EoverN>0 AND EoverN<5 THEN PRINTTAB(31)"*";1:GOT01270
1350 IF EoverP>0 AND EoverP<5 THEN PRINTTAB(31)"*";1:GOT01290
1360 IF 4<temp<PRINTTAB(49)"*";1:GOT01250
1370 IF Pressure<1000 AND Pressure>pressure_max THEN=pressure
1380 IF volflow<1000 AND volflow>vol_flow_max THEN=vol_flow
1390 IF efficiency<0 AND efficiency>efficiency_max THEN=efficiency
1400 IF temp<5 AND temp>temp_max THEN=temp
1410 IF power_load<X AND power_load>power_load_max THEN=power_load
1420 IF gas_vel<0 AND gas_vel>gas_vel_max THEN=gas_vel
1430 IF EoverN>5 AND EoverN<EoverN_max THEN=EoverN
1440 IF EoverP>5 AND EoverP<EoverP_max THEN=EoverP
1450 IF EoverP=5 THEN ENDPROC
1460 PRINT"XDischarge Electrical Laser Gas Volume*PRINT* Voltage"
1470 PRINT"Current Power Pressure Flow Rate Efficiency"
1480 PRINT"Energy Power Pressure Flow Rate Efficiency"
1490 PRINT"kW/m3 /V/cm Torr cubic m/s degC"
1500 IF=5 THEN VDU1,27,1,72
1510 ENDPROC
1520 DEF PROCtopwindow;VDU28,0,3,79,0:ENDPROC
1530 DEF PROCbottomtitle;VDU28,0,3,79,12:ENDPROC
1540 VDU1,24:PRINT"LASER VOLUME EXIT POWER*PRINT* POWER FLOW"
1550 PRINT"CURRENT TEMPERATURE LOADING/VELOCITY E/N E/P*PRINT* W CUBIC m/s degC"
1560 IF=4 THEN VDU1,27,1,72
1570 ENDPROC
1580 DEF PROCheader:IF H=5 THEN VDU1,27,1,72:INPUT$INT,$INPUT$,integ$,supply,flow,mas_flow,dates$co$ائيلاذ
1590 +FX6
1600 VDU11
1610 VDU2,1,27,1,77
1620 VDU1,27,1,71:PRINTTAB(7)"Data file name":;"1:VDU1,27,1,72:PRINTTAB(32)"$";
1630 VDU1,27,1,71:PRINTTAB(7)"Sampling interval":;"1:VDU1,27,1,72:PRINTTAB(32)"$";
1640 VDU1,27,1,71:PRINTTAB(7)"Gas supply pressure":;"1:VDU1,27,1,72:PRINTTAB(32)"$";
1650 VDU1,27,1,71:PRINTTAB(7)"Flow reading":;"1:VDU1,27,1,72:PRINTTAB(33)"$";
1660 VDU1,27,1,71:PRINTTAB(7)"Mass flow rate":;"1:VDU1,27,1,72:PRINTTAB(33)"$";
1670 VDU1,27,1,71:PRINTTAB(7)"Date and time of test":;"1:VDU1,27,1,72:PRINTTAB(33)"$";
1680 VDU1,27,1,71:PRINTTAB(7)"Comments":;"1:VDU1,27,1,72:PRINTTab$";
1690 +FX6,10
1700 VDU1,27,80,3...
1710 ENDPROC