Design considerations and scaling laws for high power convective cooled CW CO₂ lasers

A K NATH and V S GOLUBEV*
Centre for Advanced Technology, Indore 452013, India
*Scientific Research Centre for Technological Lasers, Shatura, Moscow Region, Russia
E-mail: aknath@cat.ernet.in

MS received 23 March 1998

Abstract. Various criteria for designing high power convective cooled CO₂ lasers have been discussed. Considering the saturation intensity, optical damage threshold of the optical resonator components and the small-signal gain, the scaling laws for designing high power CW CO₂ lasers have been established. In transverse flow CO₂ lasers having discharge of square cross-section, the discharge length L and its width W for a specific laser power P (Watt) and gas flow velocity V (cm/s) can be given by \( L = 1.4 \times 10^4 P^{1/2} V^{-1} \) cms and \( W = 0.04 P^{1/2} \) cms.

The optimum transmittivity of the output coupler is found to be almost constant (about 60%), independent of the small signal gain and laser power. In fast axial flow CO₂ lasers the gas flow should be divided into several discharge tubes to maintain the flow velocity within sonic limit. The discharge length in this type of laser does not depend explicitly on the laser power, instead it depends on the input power density in the discharge and the gas flow velocity. Various considerations for ensuring better laser beam quality are also discussed.

Keywords. CO₂ laser; convective cooled; design criteria, scaling laws.

PACS Nos 42.55; 42.60

1. Introduction

High power CW CO₂ lasers in the 1–25 kW range are being used extensively for various material processing applications such as cutting, welding, surface hardening, alloying and cladding. Many different exciting schemes have been devised to make compact, efficient, reliable and versatile CW CO₂ laser systems [1–7]. Many papers have described the detailed design of laser systems, still it is not obvious how to determine different parameters e.g. dimensions of the discharge volume, gas pressure and mixture, optical resonator configuration for designing a high power laser of a desired output power. Recently, Schuocker [8] has outlined the design considerations for high power co-axial CO₂ laser with fast axial gas flow and assessed the feasibility of realizing ultra-high power CO₂ lasers of 100 kW class. However, the saturation effects have not been taken into consideration in this approach due to which efficient extraction of laser power will not be feasible in this design.

In this article, first we will briefly review the laser power scaling in different types of CO₂ lasers. We will then present the design criteria and scaling laws for high power CO₂
lasers which we derived based on the design of a 5 kW transverse flow CW CO₂ laser we
developed [9, 10] and considering the saturation intensity, the optical damage threshold of
optical resonator components and the small-signal gain. The calculated design parameters
for transverse flow (TF) as well as fast axial flow (FAF) CO₂ lasers of different output
powers were calculated and compared with the practical systems reported in literature.
The theoretical and experimental design parameters match quite well.

2. Basic principle of CO₂ laser operation

Historically, the first generation CO₂ lasers were made of a single discharge tube filled with
a mixture of CO₂, N₂ and helium and fitted with a pair of electrodes for electrical excitation
and two end mirrors forming the optical resonator, as shown in figure 1a. The excitation of
the active medium was created by passing electrical discharge current through the gas
mixture. Different types of discharge such as dc, ac and rf have been used for excitation. In
the discharge, N₂ molecules are excited by energetic electrons via collisions to higher
vibration energy levels which are relatively long-lived. The excited N₂ molecules sub-
sequently transfer their energy to CO₂ molecules via collision exciting them to upper laser
level. Excited CO₂ molecules emit laser radiation through stimulated emission process and
decay down to lower laser level. From there, they come back to ground state via collision
with helium.

Though, CO₂ laser is one of the most efficient lasers, still about 80% of the electrical
power is dissipated as heat in the gas raising its temperature. The population in the lower
laser level corresponds to the Boltzmann distribution i.e. it rises exponentially with gas
temperature. Because of this the population inversion vanishes when the gas temperature
rises to 500–600°C. The maximum inversion is achieved when the temperature of the
active medium is in the range of 200–500°C. Thus, one of the fundamental requirements
for efficient laser operation is that the active medium should be promptly cooled with
some effective means.

In conventional CW CO₂ laser heat is removed via diffusion through the wall of the
glass tube which is cooled by continuous flow of water through a jacket placed around it,
figure 1a. Helium being light, it carries away heat effectively from the lasing zone to the
wall of the discharge tube which gets cooled by water. Diffusion cooling becomes less
effective with the increase of tube diameter and it has been found that the product of the
laser gas pressure and the discharge tube diameter should be maintained at a fixed value,
about 25–30 Torr-cm for optimum laser operation. Thus, the laser power can be increased
by increasing the discharge length only and the maximum power available per unit
discharge length is about 50–60 W/m.

Another very effective method developed for gas cooling is convective cooling i.e. by
flowing the hot gas out of the lasing zone and replacing with cool gas continuously at a
very fast rate. This allows CO₂ laser to be scaled up with gas flow to very high power
levels in multi-kilowatt range.

According to the methods used for laser gas cooling and stabilizing the discharge, CO₂
laser can be classified into three types. These have been illustrated in figure 1. In the first
type, figure 1a, the discharge is along the optical axis, and the cooling of the active
medium and the discharge stability are maintained by diffusion processes. While the heat
Design criteria of convective cooled CW CO$_2$ lasers

Figure 1. Schematic diagram of different types of CO$_2$ laser. Q: Heat flux, q: charged particle flux, $V_f$: gas flow velocity.

generated in the lasing zone is removed by gas diffusion to the cooled wall of the laser tube, the ambipolar diffusion of electrons prevents the discharge from contracting. Recently, a new scheme for scaling up the output power in diffusion cooled CO$_2$ laser to higher powers has been developed in which uniform and stable discharge is created between two extended electrodes [11]. Two geometries, the planar, figure 2a and the co-axial, figure 2b have been developed and output power of a few kW have been obtained. The heat from the laser gas is removed by diffusion process through the electrodes and
the laser power can be increased by increasing the area of electrodes. However, the ambipolar diffusion of electrons cannot spread the discharge over the entire volume. Usually RF discharge which has positive discharge impedance characteristics is used for maintaining uniform and stable discharge in this type of laser. In these lasers some of the CO$_2$ molecules are dissociated by electron collisions and some other gaseous products detrimental to laser action are generated in discharge-chemical reactions. In order to rejuvenate the laser gas, slow gas flow or recirculation of gas through some catalyst is incorporated in the laser.

In laser of the second type, the gas cooling is done by flowing the gas at fast speeds (convective cooling) along the optic axis and are known as fast axial flow CO$_2$ lasers, figure 1b. Discharge stabilization in this type of laser depends on the ambipolar diffusion and also on the turbulence in the gas flow.

Finally, in lasers of the third type, the laser gas is flown rapidly in a direction perpendicular to the optic axis, figure 1c. The gas residence time in the discharge is very short due to fast flow and short traverse length which does not provide enough time to discharge instabilities to constrict the discharge. However, some auxiliary methods are usually
Design criteria of convective cooled CW CO₂ lasers

required to produce and maintain uniform and stable discharge in large active volumes. Historically, resistance or capacitance ballast segmented electrodes for distributing discharge current uniformly, and auxiliary dc discharge [12], rf [5], pulser [3,6,7], corona discharge [13] or electron beam [14] have been used for sustaining main discharge current. Among various techniques, the pulser sustained discharge method has proved to be very attractive because it does not require any auxiliary electrode and it provides control on the discharge parameter \( (E/p; E, \text{electric field}, p, \text{gas pressure}) \) for maximum vibrational excitation [7]. Recently, we developed a 5 kW CO₂ laser based on this technique in which we could put maximum input power density up to 20 W/cc, the highest reported in this type of laser to our knowledge, and obtained electro-optic efficiency of nearly 15% [10].

3. Laser power scaling in various types of CO₂ laser

The output power of a laser scales up with the input power. In a CO₂ laser, the input electrical power density is limited by two factors: first is the rise in laser gas temperature, optimum being, \( \Delta T_{\text{opt}} = 200-250 \degree \text{C} \). This limits the input power density \( P_{\text{in}} \) as the following:

\[
P_{\text{in}} \leq (1 - \eta)^{-1} \cdot \rho \cdot C_p \cdot \Delta T_{\text{opt}} / t_c = P_c \quad \text{(say)},
\]

where \( \rho \) and \( C_p \) are the density and the specific heat of the laser gas respectively, \( \eta \) is the electro-optic efficiency and \( t_c \) is the gas cooling time.

Second limiting factor for the input electrical power is the discharge instability, the most common being the ionization thermal instability. In order to avoid the discharge instability, the input power density should be [15]

\[
P_{\text{in}} \leq 1/A \cdot \rho \cdot C_p \cdot \Delta T / t_s = P_s \quad \text{(say)},
\]

where \( A \) is a rate coefficient which is mainly determined by the slope of the dependence of the ionization rate on the discharge parameter \( E/p \), and \( t_s \) is the characteristic decay time for any fluctuation in the electron density. The typical value of \( A \) is about 10 for the usual laser operating conditions. For efficient and reliable laser operation the input power density should be smaller than the above two limits determined by the cooling and the discharge stabilization processes.

3.1 Diffusion cooled CO₂ laser

In a diffusion CO₂ laser, heat is conducted out mainly by helium, and the cooling time \( t_c \) in a cylindrical tube of diameter \( d \) is given by

\[
t_c = d^2 / 24D_h = d^2 / 8\lambda_c \cdot V_{\text{th}},
\]

where \( D_h \), \( \lambda_c \) and \( V_{\text{th}} \) are the diffusion coefficient, mean free path and average thermal velocity of helium, respectively.

The characteristic decay time of discharge instability \( t_s \) is determined by the ambipolar diffusion process,

\[
t_s = d^2 / 24D_a,
\]

where \( D_a \) is the electron-ion ambipolar diffusion coefficient.
\[ D_a \] is about 50 times of \( D_h \) [16], thus \( t_s \approx t_c/50 \), and from eqs (1) and (2), \( P_c \approx P_s/5 \). Therefore, the maximum input power density \( P_{\text{in}} \) is limited by the heating effect and not by the discharge instability in diffusion cooled laser.

Laser output power \( P_0 = \eta \cdot P_{\text{in}} \cdot V \), where \( V \) is the discharge volume.

\[
V = \left( \frac{\eta}{1 - \eta} \right) \frac{\rho \cdot C_p \cdot \Delta T_{\text{opt}} / t_c}{\pi d^2 / 4} \cdot L,
\]

where \( L \) is the discharge length. Substituting \( t_c \) from eq. (3),

\[
P_0 = 2\pi \cdot \left( \frac{\eta}{1 - \eta} \right) \cdot \rho \cdot \Delta T_{\text{opt}} \cdot \lambda_c \cdot V_{th} \cdot C_p \cdot L.
\]

The mean free path \( \lambda_c \) is inversely proportional to gas density \( \rho \) or pressure. Equation (6) shows that the laser power in a diffusion cooled laser in directly proportional to the discharge length and is independent of the tube diameter and the gas pressure. Substituting typical values of different parameters in the right hand side of the above expression for laser operating conditions (\( \eta = 0.1-0.2, \Delta T_{\text{opt}} = 200 \text{ K}, \lambda_c = 5 \times 10^{-4} \text{ cm}, V_{th} = 10^5 \text{ cm/s}, \rho = 0.015 \times 10^{-3} \text{ g/cc}, C_p = 2.8 \text{ J/g}^\circ \text{C} \)) one gets the maximum output power per unit length of the active medium, \( P_0/L = 50-75 \text{ W/m} \).

Thus, the laser power in a conventional diffusion cooled CO\(_2\) laser can be scaled up by increasing the active length only. High power lasers in kW output power range have been developed incorporating several discharge tubes arranged optically in series. Recently, another design has been developed which is called multibeam CO\(_2\) laser and has a large number of parallel discharge tubes placed within a common optical resonator cavity, figure 3 [17]. Each discharge tube gives its own beam, thus the output beam of the laser consists of a large number of small size, parallel beams. Industrial models of multibeam CO\(_2\) laser up to 2 kW and experimental devices up to 10 kW have been reported [18]. Though the basic design is simple, accommodating a large number of fragile discharge tubes of glass or quartz in a small area becomes cumbersome. Another drawback is that the beam quality is relatively poor because of independent multiple beams. Various techniques are being experimental to phase-lock individual beams in order to improve the beam quality [19, 20].

In a more recent development, the output power scaling with the extended discharge area has been made feasible in diffusion cooled lasers by innovative designs and laser powers in kW range have been achieved with high quality output beam, figure 2 [21, 22].
3.2 Extended electrode, diffusion cooled CO\textsubscript{2} laser

In extended electrode discharge as shown in figure 2 the laser power scales as [11]

\[ P_0 = f P_1 \cdot L \cdot W / d, \]

where \( f \approx 0.5 \), takes account of the reduced effectiveness of two walls as compared to four-wall cooling by gas diffusion in a conventional laser, \( P_1 \) is the laser power per unit length for a square cross-section of the gain medium, and \( L, W \) and \( d \) are the length, width and electrode gap respectively of the extended electrode discharge. From this, one can arrive at a simple scaling relation for the laser power per unit area of the gain medium,

\[ P_0 / S = f \cdot P_1 / d \approx 10 \text{ kW/m}^2, \quad \text{for } S = L \cdot W = 1 \text{ m}^2 \text{ i.e. } \]

\[ L = W = 1 \text{ m and } d \approx 3 \text{ mm}, \]

typical of waveguide configuration.

This indicates that high power lasers in kW power range are feasible in diffusion cooled extended electrode configuration. However, one of the problems in developing extended electrode laser is to establish uniform and stable discharge in the whole volume. DC discharge due to its negative impedance characteristics, tends to constrict in a small volume instead of spreading over the entire electrode area. Fortunately, rf discharge does not show negative impedance characteristics in the input power density range of 5–10 W/cc. Recent developments in rf discharge technology has enabled to create uniform and stable electrical discharge in extended electrode laser systems and output power in a few kW range have been reported in both planar [21] and annular electrode [22] geometries. A new method called ‘Macken discharge’ has also been developed to create uniform and stable discharge between extended electrodes with dc current stabilized by the magnetic field applied in a direction perpendicular to the current and obtained specific power of 7–8 kW/m\(^2\) [23].

The extended electrode laser systems require novel optical resonator designs to extract laser power efficiently in a beam of good mode quality, figure 2 [24, 25].

3.3 Convective cooled CO\textsubscript{2} lasers

In convective cooled CO\textsubscript{2} lasers, cooling of the active medium depends upon the gas flow rate. The gas flow and the turbulence in it also influence the growth of the ionization-thermal instability. The characteristic cooling time \( t_c \) and decay time \( t_s \) of the thermal instability can be given by

\[ t_c = H / V_f = t_f, \quad \text{(7a)} \]

\[ 1 / t_s = 1 / t_d + V_f / H + V_t / l_t \]

\[ = 1 / t_d + 1 / t_f + 1 / t_i, \quad \text{(7b)} \]

where \( t_d \) is the characteristic time constant for ambipolar diffusion, \( V_f \) is the gas flow velocity, \( H \) is the discharge length along the gas flow, \( V_t \) is the turbulence velocity, and \( l_t \) is the typical turbulence dimension.
Typical values of different time constants in convective cooled CO₂ lasers are

\[ t_d = 10^{-2} - 10^{-3} \text{ s}, \]
\[ t_f = 10^{-3} - 10^{-4} \text{ s}, \]
\[ t_t \approx t_f, \]

\( t_d \) being larger than \( t_f \) and \( t_t \), the decay time of thermal instability \( t_s \leq t_f \) depending upon the turbulence. In a transverse flow CO₂ laser, turbulence is usually not very strong, therefore \( t_s \approx t_f \). For \( A \approx 10 \) as mentioned earlier,

\[ P_s \approx P_c/10. \]

This indicates that in transverse flow laser, the discharge instability limits the maximum input power density. However, in fast axial flow lasers, particularly those excited by dc discharge, strong turbulence is deliberately created for discharge stability. This makes \( t_s < t_f \), which in turn, results \( P_c < P_s \). Thus, in FAF CO₂ lasers the input power density is not limited by the discharge instability, instead it is determined by the heating effect and its maximum value is more than that in TF CO₂ lasers.

In transverse flow lasers with large discharge electrode area the ambipolar diffusion process alone cannot maintain uniform and stable discharge in the entire volume and therefore, different auxiliary schemes such as segmented electrodes and partial ionization of active medium by either auxiliary dc discharge, corona discharge, electron beam, rf or high voltage pulses are employed. Depending upon the stability ensured by a particular scheme, the maximum input power density ranges from 5–50 W/cc. Comparison of the performance of various schemes has been presented in figure 4. Among various schemes for sustaining dc discharge, the high voltage high repetition rate pulser sustained dc discharge excitation technique has proved highly promising, allowing high input power densities in the discharge. Also shown in figure 4 are the typical values of input power densities in rf excited FAF and TF lasers. RF discharge, having positive discharge impedance characteristics, ensures better discharge stability, therefore, can be operated with higher input power densities compared to dc excitation as shown in figure 4. And, FAF laser, due to the strong turbulent gas flow in it, can withstand higher input power densities than TF laser as discussed earlier.

The laser output power in a convective cooled laser can be estimated from the following relation:

\[ P_0 = \eta \cdot P_{in} \cdot V, \quad \text{where } V \text{ is the discharge volume} \]
\[ = \left[ \eta / 1 - \eta \right][\rho C_p \Delta T_{opt}/t_f] \text{ WHL, (figure 1c),} \]  
\[ tf = H/V_f \text{ in transverse flow laser} \]
\[ = L/V_f \text{ in fast axial flow laser.} \]

Thus,

\[ P_0 = \left[ \eta / 1 - \eta \right] C_p \Delta TM, \]

where \( M \) is the mass flow rate = \( \rho \cdot V_f \cdot S \), and \( S \) is the area of the flow aperture. For typical laser conditions, \( \eta \approx 0.15 \), \( C_p = 2.8 \text{ J/g°C} \), \( \Delta T = 250°C \) we get

\[ P_0 = 120M \text{ Watts,} \]

where \( M \) is in g/s.
The above laser power scaling law indicates that the output power in a convective cooled CO$_2$ laser is proportional to the gas mass flow rate or the gas flow velocity.

Referring to eq. (8), it can be seen that for the same rise in gas temperature, the laser power per unit discharge length is much higher in transverse flow CO$_2$ laser due to shorter gas residence time than those in axial flow CO$_2$ lasers. The typical values in transverse and axial flow lasers are 5–10 kW/m and 1–3 kW/m respectively. Moreover, axial flow lasers due to their narrow flow apertures require special types of gas circulating blowers with high pressure heads (roots or high speed turbo blowers) while transverse flow lasers with their large flow aperture will require ordinary blowers (eg. axial or centrifugal blowers) with moderate pressure head. Thus, the transverse flow configuration is better suited for laser power scaling to higher power levels. However, axial flow configuration has an edge over transverse flow configuration in terms of beam quality. In axial flow laser the discharge, which is usually confined in a cylindrical tube, has circular symmetry and can support better quality laser beam while such symmetry lacks in transverse flow lasers due to cross gas flow. Development of both types of laser has been
pursued vigorously, and axial flow CO₂ lasers up to 20 kW [26] and transverse flow CO₂ lasers up to 50 kW [27] have been reported.

4. Design considerations

In order to design a CO₂ laser of a given output power, the physical dimensions of the active volume, gas flow velocity, output coupling of optical resonator are to be decided.

If we know the typical input power density \( P_{\text{in}} \) which can be dissipated in the homogeneous and stable discharge, the required volume of the active medium for the desired output power \( P_0 \) can be known from eq. (8). \( P_{\text{in}} \) depends on several factors such as electrode design, gas mixture and its pressure, method of excitation, and gas flow velocity and its uniformity. With the typical gas flow velocity \( \sim 50-200 \, \text{m/s} \), this is in 5–50 W/cc range, figure 4, higher values are usually for RF excited lasers, and the lower values are for large discharge volume systems. The required gas volumetric flow \( Q = M/p \) can also be calculated using eq. (9) for a given \( P_0 \).

Following considerations can be taken into account in determining the design parameters such as the discharge length, discharge aperture, optimum reflectivity and gas pressure.

(i) The maximum intracavity laser power density should be less than the damage threshold of optical elements, however, it should be more than the saturation intensity \( I_s \). \( I_s \) is proportional to \( p^n \) where \( p \) is gas pressure in mbar and \( n = 2 \) in slow flow lasers and is between 1 and 2 in fast flow laser systems wherein the gas residence time is comparable to the collisional relaxation time of the upper laser level [28].

(ii) The damage threshold intensity of the ZnSe mirror, usually used as output coupler in CO₂ lasers is about 2 kW/cm². Considering this the intracavity intensity, \( I_c \) incident on the output coupler should be maintained at around 1.0 kW/cm². Assuming a square cross-section of the discharge zone one can write for a reasonably good gain volume to mode volume overlap

\[
P_0 = W^2 \cdot I_c \cdot T,
\]

where \( T \) is the transmittivity of output coupler or,

\[
W = 0.032 \left( P_0 \text{Watts}/T \right)^{1/2} \text{cm}.
\]

(iii) The optimum output coupling or transmittivity of the resonator can be estimated with the knowledge of the small signal gain \( g_0 \) and the intracavity losses \( a \) by the following relation [29].

\[
T_{\text{opt}} = 1 - \exp[-2L \left( (g_0 \cdot a)^{1/2} - a \right)].
\]

The small signal gain is usually experimentally measured and it is in the range of 0.5–1% per cm. It can be estimated also by the following relation with reasonable accuracy [30].

\[
g_0 = 10P_{\text{in}} \cdot f/p^2,
\]
Design criteria of convective cooled CW CO₂ lasers

where \( f = N_c/[N_c \cdot t/t_f + (N_c + 1/k \cdot t_f)] \), \( N_c \) and \( N_n \) are the molecular densities of CO₂ and \( N_2 \) respectively, \( k \) is the CO₂–N₂ energy transfer coefficient, and \( t \) is the non-radiative (including the effect of fast gas flow) decay time constant of CO₂ (001) level. Factor \( f \) accounts for the energy stored in \( N_2 \) molecules which takes some finite time to get transferred to CO₂ molecules, and is more than 1 in fast gas flow lasers.

In optimum laser design it can be seen that the transmittivity \( T \) is almost constant, independent of small signal gain and the laser power. We can write for the intracavity intensity \( I_c \) incident on the output coupler

\[
I_c = I_s \cdot g_0 \cdot L \quad \text{or} \quad g_0 \cdot L = I_c/I_s.
\]

The maximum value of \( I_c \) is limited by the damage threshold of the output coupler and thus the maximum value of \( g_0 \cdot L \) is also limited. In the optimum laser design the intracavity losses \( a \cdot L \) is kept minimum and this is also independent of laser power. Usually the total intracavity loss is not more than 5% of total gain. Thus, \( g_0L \) and \( aL \) being constant, the optimum transmittivity \( T_{\text{opt}} \) is also constant. For the typical values of \( I_s \) and \( I_c \) about 300–500 W/cm² and 1 kW/cm² respectively, \( g_0L \) is in the range of 2–3 in high power lasers. For these conditions,

\[
T_{\text{opt}} \approx 50–60\%.
\]  

(iv) The limitation imposed on the saturation intensity that it should be less than the intracavity laser intensity limits the operating pressure within about 100 mbar.

From eqs (8), (10) and (11) we get for transverse flow lasers

\[
W \approx 0.04(P_0)^{1/2}\text{cm}
\]

and

\[
L = 1.4 \times 10^4V_f^{-1} \cdot (P_0)^{1/2}\text{cm},
\]

for \( V_f \) in cm/s and \( P_0 \) in Watt.

In transverse flow lasers, usually–folded optical resonator is used to make the system compact. There are two configurations of folded optical path with respect to the direction of gas flow. One having optical path folded transverse to the flow (OPTF), figure 5a, another having folds along the flow (OPAF), figure 5b. Apparently, the first configuration is better than the second one because it imposes relatively less impedance to the gas flow and also because it will allow relatively high input power densities for a given flow velocity due to shorter gas residence time. Since folding mirrors introduce extra losses, number of folding should be kept minimum. Laser output power with \( N \) optical path folds in OPTF configuration can be given by (eq. (8) and figure 5a)

\[
P_0 = KV_f LH = KV_f LNW,
\]

where

\[
K = (\eta/1 - \eta) \cdot \rho \cdot C_p \cdot \Delta T
\]

Substituting \( H \) from eq. (12) we get

\[
L = 30(P_0)^{1/2}/KNV_f.
\]
In case of OPAF configuration, figure 5b we get

\[ L = 30(P_0)^{1/2}/KV_f. \]  \hspace{1cm} (15)

From eqs (14) and (15) it is obvious that the active length in OPTF configuration is \( N \) times smaller than that in OPAF configuration for the same flow velocity and a given laser output power. Thus, the OPTF configuration is better for designing high power lasers of compact size. The flow velocity is determined by the available blowers. In TF lasers usually fast axial blowers or centrifugal blowers are used and the typical flow velocity is in the range of 50–100 m/s. Accordingly, the active length can be determined by the above equations.

(v) Another criterion which should be considered is that the diffraction loss should be minimum in the resonator. For this, the factor \( \eta_F \) which is a function of Fresnel number, should be less than unity, i.e. \( \eta_F = 4\lambda L/W^2 \ll 1 \), where \( \lambda \) is the laser wavelength.

In case of fast axial flow CO\(_2\) laser the dimension of the laser tube diameter can be determined with the same criteria as \( W \) has been determined using eq. (12). The discharge tube aperture area will be proportional to the required output power \( P_0 \). From eqs (8) and (12) we get

\[ V_f \approx 1000 \text{ m/s}. \]

This reveals certain interesting aspects regarding the design of FAF laser. The gas flow velocity \( V_f \) is independent of the laser power \( P_0 \) and the later one does not seem to depend on the discharge length explicitly. However, the volumetric flow has to be increased proportional to \( P_0 \) or the tube aperture area. The required \( V_f \) of about 1000 m/s is in the supersonic range. Such high velocities drastically increase the pressure head requirement of the gas blowers and also the acoustic noise. These problems can be circumvented by dividing the gas flow through a large number of discharge tubes maintaining the flow velocity in the range of 150–250 m/s through each tube. In practical systems 4–8 discharge sections should be used depending upon the maximum flow velocity one can get through each section, figure 6. Specially designed roots blower or high speed turbo-blowers are
Design criteria of convective cooled CW CO₂ lasers

Figure 6. Schematic diagram of a rf excited fast axial flow CW CO₂ laser with six discharge sections.

normally required to circulate the laser gas through the discharge tubes and heat exchangers in this configuration.

In the optimum design, the gas emerging out of each discharge tube should be heated up to the optimum temperature ΔT_{opt}, and this will depend on the input power density P_{in} and the discharge length L for a given gas flow velocity. The discharge length can be calculated using the energy balance equation:

\[ L = \frac{\rho C_p \Delta T_{opt} V_f}{(1 - \eta) P_{in}}. \]  \hspace{2cm} (16)

P_{in} depends on the excitation scheme (dc or rf) employed and flow characteristics (turbulent or laminar) and is typically in the range of 10–50 W/cc.

For the typical operating conditions in a rf excited FAF laser (V_f = 150 m/s, \eta = 20\%, \Delta T_{opt} = 250 K, \rho \approx 3 \times 10^{-5} \text{ g/cc} (p \approx 100 \text{ mbar}), C_p \approx 2.8 \text{ J/g K}, P_{in} = 20 \text{ W/cc}) the discharge length L is about 20 cms. And, the optimum transmittivity of the output coupling mirror is the same as for the TF laser.

One of the important factors in high power CO₂ laser is its beam quality. A high quality laser beam must have the phase of the radiation uniform over its cross-section. Such
beams can be focused very tightly which is often desired in laser cutting, drilling and welding applications. In convective cooled lasers the non-uniformity in gas flow and presence of turbulence and the non-uniformity in electrical discharge and gas heating cause inhomogeneity in the gas density and the refractive index [31]. These factors, in return cause distortion in the phase front of the laser beam. The aberration in phase front depends on the spatial scale of turbulence, deviation in refractive index and the dimension of the active medium in which turbulence is present [32]. The factors which affect discharge uniformity and stability such as geometrical inhomogeneities of electrode system, non-uniformities in gas flow and turbulence, and formation of negative ions should be minimized while designing the laser system. The pulser sustained dc discharge allows relatively higher input power densities in the discharge, figure 4, therefore the laser based on this technique will have relatively smaller active volume and will support better beam quality. The laser beam propagates transverse to the gas flow and quite often also to the applied electric field between anode and cathode in the TF configuration. The gain is usually not symmetric along the direction of gas flow and the dc electric field. Therefore, TF lasers should be designed with even number of beam paths in OFTF configuration and the beam should be folded in such a judicious manner that the effect of any asymmetry in the gain medium on the phase front of the laser beam gets canceled.

5. Comparison with experimental laser systems

We have developed a transverse flow pulser sustained dc excited CW CO\textsubscript{2} laser, having folded optical resonator in OPTF configuration, figure 7 [9,10]. This has an active length of 180 cms created between a pair of multiple pins, anodes and a common cathode with 30 mm inter-electrode separation. The gas flow velocity is about 50 m/s and a maximum input power density of about 20 W/cc is deposited maintaining uniform and stable discharge in a typical laser gas mixture (CO\textsubscript{2} : N\textsubscript{2} : He = 1 : 7 : 15) at 45–50 mbar pressure. Maximum laser power of 5.2 kW has been obtained with an optimum output coupling of 60%. The electro-optic efficiency is nearly 15%.

Table 1 presents the comparison between the calculated and actual values of $L$, $H$, $T$ of the above laser and a 20 kW TF laser system [33]. Various design parameters of a dc excited [34] and a rf excited [35] FAF lasers are presented in table 2 along with their calculated values. Comparisons in both TF and FAF lasers show very good agreement between the experimental and calculated values of design parameters confirming the validity of the design criteria and scaling laws described above.

On the basis of the above design criteria we are now developing a rf excited FAF CW CO\textsubscript{2} laser having six discharge sections, each of 20 cms discharge length and 22 mm inner diameter, figure 6. We have obtained about 100 m/s flow velocity through each tube with the help of a high speed centrifugal blower operated at 10000 rpm. According to eq. (16) we should be able to dissipate about 12 W/cc input power density in the discharge at this flow velocity and obtain about 650 W total laser power i.e. nearly 110 W output power per discharge tube at 15% electro-optic efficiency. In an initial experiment we operated two sections as a laser with rf excitation at 5 MHz frequency. We obtained maximum 160 W laser power which was limited by the gas flow velocity [36]. At this operating condition the
Design criteria of convective cooled CW CO₂ lasers

Figure 7. Schematic diagram of a 5 kW transverse flow CW CO₂ laser.

Table 1. Comparison of experimental and calculated design parameters of some transverse flow CO₂ lasers.

<table>
<thead>
<tr>
<th>Laser power (kW)</th>
<th>Flow velocity (m/s)</th>
<th>Experimental</th>
<th>Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L (cm)</td>
<td>H (cm)</td>
<td>T&lt;sub&gt;opt&lt;/sub&gt;%</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>180</td>
<td>3.0</td>
</tr>
<tr>
<td>20</td>
<td>80</td>
<td>280</td>
<td>6.5</td>
</tr>
</tbody>
</table>

Table 2. Comparison of experimental and calculated design parameters of some fast axial flow CO₂ lasers.

<table>
<thead>
<tr>
<th>Laser power kW</th>
<th>Flow velocity m/s</th>
<th>Number of discharge sections</th>
<th>Length of each section (cm)</th>
<th>Discharge tube diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>160</td>
<td>8</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>3.7</td>
<td>140</td>
<td>8</td>
<td>8</td>
<td>18</td>
</tr>
</tbody>
</table>

input power density was about 10 W/cc and the electro-optic efficiency was nearly 13%. We expect to obtain laser power very close to the designed value once all discharge sections are made operational and various experimental parameters are optimized.
6. Conclusion

Power scaling in different types of CO2 lasers and recent technological developments indicate that diffusion cooled CO2 lasers can be scaled up to a few kW level and the convective cooled (axial as well as transverse flow) CO2 lasers can be scaled up to a few tens of kW level. The pulser-sustained dc excited, transverse flow configuration with optical path folded across the gas flow offers a simple and compact design for very high power CO2 lasers with good beam quality. The design criteria presented here provide guidelines to determine various physical and optical parameters of convective cooled CO2 lasers of the desired output power.

Acknowledgements

The author (VSG) wishes to acknowledge his gratitude to D D Bhawalkar for inviting him to CAT, Indore, where during his stay this work was done. The dedicated efforts of the high power CO2 laser group of CAT in the development of high power CO2 lasers is greatly appreciated.

References

Design criteria of convective cooled CW CO₂ lasers

[27] L M Holmes (Ed), Laser Focus World (PennWell Publication, 1991) 27, 44