Fluid Dynamics in Closed-Cycle Pulsed Lasers

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I. Introduction

SEVERAL types of repetitively pulsed gas lasers use closed-cycle flow systems to minimize gas consumption, eliminate exhaust, and provide minimum weight laser systems for long run time applications. These lasers span the spectrum from infrared to ultraviolet with output pulse lengths from tens of milliseconds down to tens of nanoseconds. Pulse repetition rates as high as 1500 Hz have been demonstrated.

A closed cycle is used with CO_2 lasers to minimize gas consumption and system weight for long run times. Axial discharge CO_2 lasers up to 5 kW output power with recirculated axial flow are commercially manufactured for industrial applications. However, this paper will concern only transverse flow lasers whose flow, optical, and excitation axes are orthogonally disposed. Several pulsed electric discharge CO_2 lasers have been reported with recirculating transverse flow systems.[1-5] Commercially manufactured pulsed CO_2 closed-cycle lasers with transverse flow are used as laboratory sources. Pulsed CO_2 closed-cycle lasers have also been developed for Lidar applications.[6-7]

Closed-cycle recirculation systems have also been added to pulsed HF/DF chemical lasers to reduce gas consumption and eliminate noxious effluents.[8-10] These discharge-initiated lasers incorporate chemical scrubbers to remove chemical reaction products.

Closed-cycle gas recirculation systems are used to allow high output power and to conserve expensive rare gas mixtures in pulsed excimer lasers. Several closed-cycle excimer laser systems have been described in the literature,[11-17] and small closed-cycle ArF, KrF, XeCl, XeF lasers are commercially available. These excimer lasers are used for spectroscopic studies, to pump dye lasers, and for materials processing with ultraviolet radiation.

A closed-cycle recirculation system must efficiently supply laser gas with the correct properties and adequate medium homogeneity to the repetitively pulsed laser cavity. The system must remove detrimental chemical contaminants and replace chemical components consumed in the laser reaction or in wall reactions. Flow system component reliability and gas lifetime are critical issues for long run applications.

The flow system must provide flowing gas to the laser cavity with sufficient medium homogeneity to allow the desired output optical quality and to assure discharge or reaction uniformity. Index of reflaction disturbances resulting from density or composition nonuniformites exponentially degrade optical quality and Strehl ratio. The density nonuniformity must be maintained below a level on the order of 10^{-4} to provide a 90% Strehl ratio over a 1 m path length in a typical XeCl mixture. This homogeneity requirement scales with the ratio of the wavelength to the path length.[18]

Electrical discharge stability is sensitive to disturbances in the E/n parameter caused by density nonuniformities in the discharge cavity.[19] Density nonuniformities must be kept below 1% to assure discharge stability in a typical discharge geometry.[20]

High laser system efficiency requires efficient movement of the lasing gas around the closed loop. The gas mixture, cavity volume, repetition rate, and optical length are determined by the desired laser output requirements. Discharge or excitation requirements specify the cavity pressure and excitation height. However, fluid mechanical design controls the cavity flow velocity and the power required to circulate the flow.

The pulsed power system controls the efficiency of laser systems with small output apertures or low pulse repetition rates. Fluid dynamic design becomes more important for larger laser devices. For a given aperture width, the efficiency of a flow system is directly related to its size since the individual component pressure drops are proportional to the inverse square of the local flow area. A well-balanced flow system design allocates volume and pressure drop to best obtain particular design goals.

In this paper, typical closed-cycle flow systems for pulsed lasers, their individual components, and some techniques used to design and model them are described. Unsteady flow

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phenomena are considered, with some techniques used to analyze them and methods developed to control them. Several flow system issues that offer improvements in the performance of closed-cycle pulsed laser systems are discussed in the final section.

II. Baseline Flow

Flow-Loop Description

The closed-cycle laser flow system is similar to a subsonic wind tunnel but differs because of laser cavity geometry, the presence of large unsteady heat additions, and the requirement for very uniform cavity flow homogeneity. The cavity flow velocity is oriented transverse to the optical and excitation axes to minimize the Mach number required to exchange the cavity gas between pulses. The large ratio of optical cavity length to excitation height typical of an optical cavity requires a very high aspect ratio flow cavity.

The flow-loop geometry is determined by the manner in which the high aspect ratio cavity flow is integrated with the rest of the loop components. Two generic flow-loop configurations are shown in Fig. 1. The external-type flow loop can be assembled using conventional components. The cavity flow passes through a diffuser and acoustic damper to an axial or centrifugal circulator. The heat exchanger, which may be split into two sections, is located downstream of the circulator to smooth and condition the flow prior to cavity entry through an upstream acoustic damper and nozzle. The external configuration offers design flexibility and measurement accessibility during development, but it incorporates large volumes and surface areas that require extensive structural ribs and gussets.

The internal flow-loop configuration integrates the components into a compact cylindrical pressure vessel. Scaling in the optical direction can provide the necessary high flow aspect ratio. A transverse or cross-flow fan is well matched to this high flow aspect ratio. The unique flow-loop components must all be specially designed in an integrated manner, and several of them require further development. The internal-type flow-loop configuration offers potential for the advanced design of closed-cycle pulsed laser flow systems.

Circulator

The circulator must efficiently provide lift to balance the pressure drop incurred in the flow system. It must operate in a stable manner in the unsteady flow environment. The integration of the circulator, its drive system, and its seals strongly influence the flow-loop geometry. The circulator construction must be consistent with chemical compatibility requirements for materials or plating. Finally, the circulator design should be well developed and commercially available.

The operational characteristics of three types of flow circulators available for closed-cycle laser flow systems are shown qualitatively in Fig. 2. Several applications of axial circulators to closed-cycle lasers have been reported.[2,11-14,21] Although these circulators are very efficient, they can be susceptible to stall in unsteady flow as pressure waves drive them into off-design conditions. Long transition sections are required for efficient operation and the drive system requires two rotating seals unless the bearings are exposed to the laser gas. Axial circulators are complex and difficult to fabricate from compatible materials or to plate if chemical compatibility is an issue.

The construction of centrifugal circulators is simpler and more amenable to compatible fabrication or plating. The centrifugal design incorporates one of the required flow-loop turns. Bearings can be both chemically and thermally isolated with the use of one rotating shaft seal. As indicated in Fig. 2, the centrifugal circulator is more tolerant of unsteady flow perturbations. Centrifugal circulators are commercially available and have been used in several closed-cycle laser flow systems.[1,4,17]

Neither axial nor centrifugal circulators can easily be integrated with the high aspect ratio flow cavity in a compact design. A long, cylindrical, flexible vane fan has been used in a pulsed CO_2 laser.[7] Compatibility and wear would limit use in a long-life excimer laser, however. Cross-flow or transverse circulators shown in Fig. 3 are being applied to high aspect ratio flow geometries.[22,23] These circulators can be scaled in the direction normal to the figure. The flow enters the rotor cascade along the length of the rotor axis and passes through the cascade twice under the influence of the trapped vortex. These circulators are commercially available on a very limited scale at present. Analyses and experiments indicate that these circulators are capable of delivering high lift and large flow rates; however, performance is found to be very sensitive to the design of the flow housing.[22,23] Further development of the fluid dynamic analyses of transverse circulators is necessary.

The structural dynamics of transverse circulators is also a critical issue. Tests have shown that a central axle shaft detrimentally interferes with vortex generation and flow performance.[22] The critical speed of the complex rotor structure

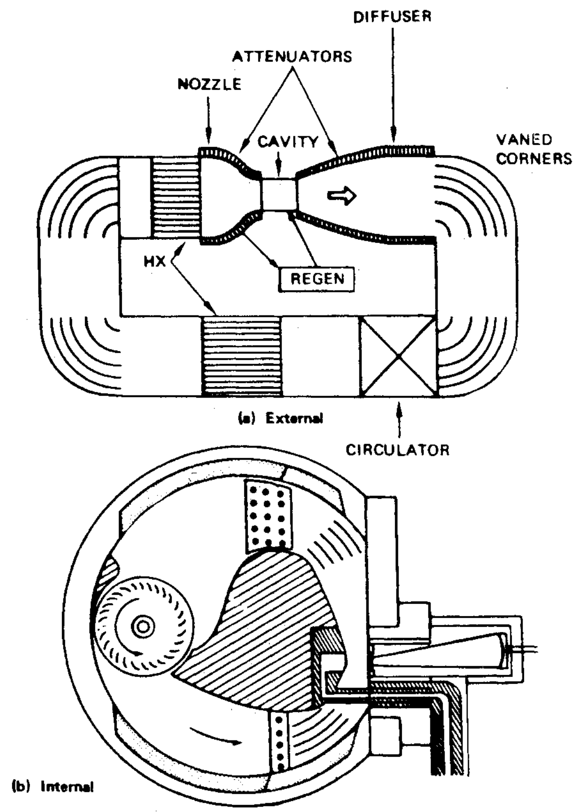

Fig. 1 Closed-cycle transverse flow laser configurations.

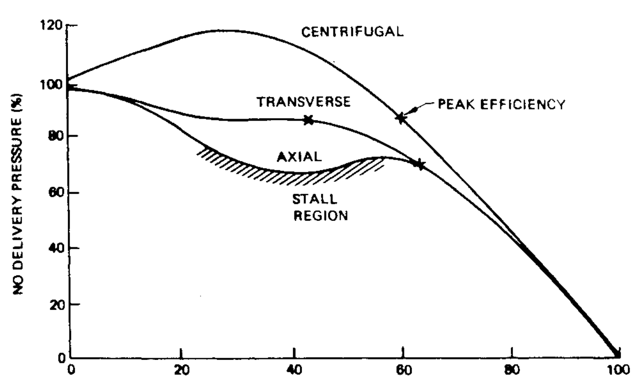

Fig. 2 Flow-loop circulator operating characteristics.

limits the unsupported length of any one circulator element. Complex shielded internal bearings may be required in some laser gases. The available commercial rotors suffer low critical speeds because of swaged blade attachment to the hubs. Higher critical speeds can be obtained with more expensive brazing or welding in this area.

Transverse circulators can be fabricated from compatible materials or plated without undue difficulty. The transverse circulator is well suited to closed-cycle laser flow systems. It needs some further development, particularly in scaling to larger sizes and wider commercial availability.

Circulator performance in the unsteady flow environment of a closed-cycle laser flow loop also needs further study. After passing through the attenuators, the wavelength of pressure disturbances in an excimer laser will be much larger than the characteristic dimension of the circulator, and the fluid displacement associated with the pressure wave will be much smaller than this characteristic dimension. In a high-repetition-rate excimer laser, the width of thermal disturbances flowing downstream will also be much smaller than the characteristic dimension of the circulator. For excimer lasers the attainment of the stringent cavity medium homogeneity requirement will assure sufficiently steady flow at the circulator. However, the effect of initial pressure wave strength can be important in low-repetition-rate systems that utilize several passes through the acoustic damper to attenuate the pressure waves in the cavity. Attenuator and circulator placement must be carefully designed in such systems.

Noise measurements for commercial circulators are not normally taken internal to flow ducts. Some data taken in the exhaust duct of a centrifugal fan of the type and size appropriate for a large closed-cycle laser system indicate pressure disturbances of less than 0.01%. These disturbances must pass through the heat exchanger and attenuator before reaching the cavity.

A rotating shaft seal is required to bring power into the circulator. This seal should have minimal leakage and be chemically and thermally compatible for long-life operation. Four types of seals have been used in closed-cycle laser systems. A face seal allows finite leakage and wear. Complex dynamic face seals have been designed to minimize these effects, but all face seals exhibit limited chemical and thermal compatibility. The thermal and chemical compatibility of labryinth seals are quite good, but they also allow finite leakage and require critical shaft alignment. Ferro-fluidic seals prevent leakage but have limited chemical and thermal compatibility. Custom designs have relaxed the critical alignment requirements for ferro-fluidic seals. Magnetic couplings also prevent leakage, but they must be used with bearings internal to the flow loop and are commercially available only in limited sizes. Currently, magnetic couplings and internal bearings lubricated with compatible greases are used in small closed-cycle laser systems. Ferro-fluidic seals or labryinths backed by ferro-fluidics are well suited for larger lasers, particularly those using high-temperature or corrosive gases.

Heat Exchanger

A heat exchanger is required in the closed-cycle flow loop to remove the thermal energy put into the gas by laser inefficiency and circulator power. The design of the heat exchanger is controlled by considerations of flow homogeneity, size, and power expended in the flow circulator and coolant pumps. Construction and materials are chosen to satisfy chemical compatibility requirements.

Three types of gas-liquid heat exchangers can be used in closed-cycle laser systems. The tube-and-shell type offers ease of plating or manufacture using gas compatible materials.[24] The tube-and-fin type is more compact and is more easily integrated with the high aspect-ratio flow loop.[13,14,17] The plate-and-fin type is more complex. Its fins must be designed to support coolant passages in a low pressure drop design.

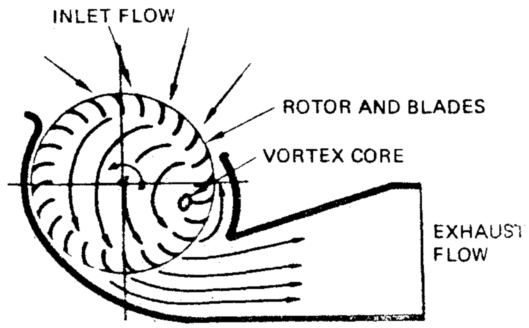

Fig. 3 Transverse circulator flow.

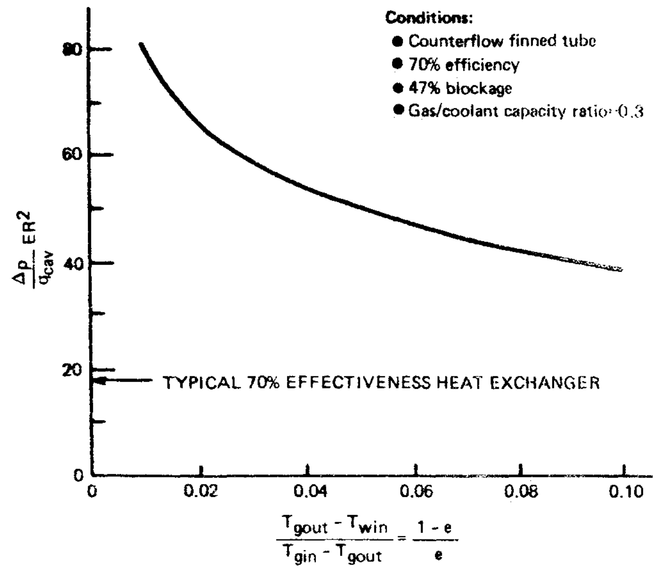

Fig. 4 Effect of final pass gas coolant temperature difference on heat exchanger pressure drop.

Although conventional design analyses are used, the design is controlled by the exhaust thermal uniformity requirement that is not normally considered in heat exchanger design. This thermal uniformity can be related to the heat exchanger design parameters in a counterflow configuration.

$$\frac{\Delta T}{T} \propto \frac{T(\text{gas exit}) - T(\text{coolant inlet})}{T(\text{gas exit})}$$

$$\propto \frac{1-e}{e} \cdot \frac{T(\text{gas inlet}) - T(\text{gas exit})}{T(\text{gas exit})} \qquad (1)$$

The allowable exhaust temperature variation is much less than the overall temperature change in a closed-cycle laser heat exhanger so that a high effectiveness e is required.

Conventional design analyses describe how heat exchanger effectiveness increases with heat exchanger length and gas side pressure drop. By casting this relationship in terms of $(1-e)/e$ the increase in pressure drop required to improve thermal uniformity can be developed, as shown in Fig. 4. This figure was generated for the condition shown in the figure, typical for closed-cycle excimer laser operation. The heat exchanger typically represents the largest component pressure drop in the flow loop. The area expansion ratio ER can be increased to lower the pressure drop illustrating the trade-off between flow-loop size and circulator power. A realistic balance must also be chosen between gas and coolant pumping power.

Turbulent mixing downstream of the heat exchanger lowers the temperature variation in the exhaust flow and allows a lower effectiveness design. Split heat exchanger designs are presently being optimized in which a low-effectiveness upstream unit using a low-temperature coolant extracts the majority of the heat. Thermal smoothing is provided in the turbulent wakes. A downstream thermalizer, which extracts little if any power, can provide the required thermal uniformity with moderate effectiveness and pressure drop.

The transient response of the heat exchanger to unsteady flow conditions has been modeled using conventional analyses. A small pressure disturbance induces large velocity variations in subsonic flow that change the heat transfer characteristics, but high effectiveness heat exchangers are less sensitive to this effect. A pressure variation of 0.8% can induce a 0.4% change in exhaust temperature in a typical closed-cycle excimer heat exchanger. The passage of a hot/cold interface also changes the heat transfer characteristics. Again, high effectiveness heat exchangers are less sensitive. An inlet temperature variation of 18% is required to produce a 0.4% exhaust temperature variation in a typical closed-cycle excimer heat exchanger.

Depending upon the application, copper, stainless steel, nickel, or plated heat exchangers are used in closed-cycle laser flow systems. Particular attention must be given to the brazing or welding techniques used.

Duct Design

Flow pumping power varies as the square of the flow velocity through the loop components. To decrease power requirements, the flow is decelerated through a diffuser, passed through loop components, then accelerated through a nozzle to return to the cavity. A high-aspect-ratio two-dimensional diffuser is well integrated with the high-aspect-ratio cavity flow.[17] A conservative 8-deg total wedge angle is used to provide stable pressure recovery in the unsteady flowfield. Separated regions of heated gas adjacent to the electrodes must be prevented to allow discharge stability. A single splitter plate can be used to shorten the diffuser and allow the use of sidewall acoustic damping. The diffuser expansion reflects pulse-generated pressure waves as rarefaction waves helping to clear the cavity. A rapid expansion immediately downstream of the cavity that has also been used for reasons of acoustic management[25, 26] is described in Sec. III.

Corners and turns in the duct work are provided with vanes to allow compact turns and to reduce secondary flows and pressure drop. Turning vanes and current returns must be located far enough upstream that their wakes do not adversely affect flow homogeneity and hot gas clearing in the cavity.

The nozzle contour has been designed using a hodograph technique that provides smooth acceleration of subsonic flows without separation and unsteadiness.[17] The wall streamline is continuously accelerated, avoiding unfavorable pressure gradients in regions of high wall curvature at the nozzle entrance and exit, which could lead to boundary-layer separation and reversed flow regions. Such separated regions could interact with the mean flow and with pulse-generated pressure fluctuations to introduce medium nonuniformities that would be convected through the cavity. The analytic flow contour can be smoothly joined to electrode contours, with due attention given to electrode edge effect. The high-apect-ratio two-dimensional nozzle can incorporate sidewall damping.

The nozzle helps to thin the boundary layer upstream of the cavity. It reduces the strength of the upstream running pressure waves and attendant entropy waves and reduces freestream turbulence levels before entering the cavity. Freestream turbulent density fluctuations scale as the square of the product of the cavity Mach number and velocity fluctuation. Conventional wind tunnel turbulence management techniques may be required for large closed-cycle excimer laser systems.

Boundary-layer calculations using integral methods show that from 3 to 10% of the cavity flow near the walls is not suitable for power extraction because of unacceptable density gradients. Less flow power is required to remove these boundary layers than the excitation power that would be wasted in them. Boundary-layer removal also aids foil cooling.

The effect of unsteady boundary-layer growth over an upstream damper on cavity optical quality is not presently clear. Thermal mismatch and jet formation in this region can disturb the freestream density quite far from the wall. Such disturbances have been measured in the baseline flow,[27] but no unsteady two-dimensional analysis has been performed.

Nozzle contours have been developed that act as an acoustic horn to minimize the clearing of small-amplitude density disturbances in near diffraction limited excimer lasers.[29] These contours were carefully designed to produce optically correctable steady flow cavity density profiles. Other work has demonstrated that downstream acoustic horns contingent with the cavity adversely affect wave clearing in pulsed CO_2 lasers. This will be discussed further in Sec. III.

Depending upon the gas mixtures, flow ducts have been constructed of plastics, aluminum, stainless steel, nickel, and plated steels. High-pressure operation requires adequate bracing and gussetting of wall sections. Thermocouple controlled wall resistance heaters and thermal insulation have been used in high-temperature systems.

Purge Flows and Gas Regeneration

It is necessary to regenerate or replace a small fraction of the flow to provide long life operation of closed-cycle lasers. Unavoidable surface reactions in excimer lasers and volume reactions associated with the laser pulse in both excimer and CO_2 lasers consume laser species and introduce undesirable reaction products. Several percent of the CO_2 laser flow rate is typically discarded and replaced with a fresh gas mixture. The reaction products are removed by passing all of the closed cycle chemical laser flow through a chemical scrubber.[10]

Studies have addressed the combined materials compatibility and regeneration issues in closed-cycle excimer lasers.[30] The output windows have proved to be particularly sensitive to contamination.[13] Several percent of the gas flow is typically drawn from the preionizer region and upstream damper regions or taken from the boundary-layer bleed and passed through a regeneration loop.

The purification is performed in a heated getter trap,[30,31] in a heated calcium trap,[30] with a chemical sieve,[30] or by cryogenic fractionalization.[32] The latter two techniques offer the possibility of selective regeneration. The purified flow has been used to purge the laser windows and to provide circulator shaft seal purge flow. Active species must be reintroduced to the flow stream and well mixed prior to reaching the cavity.

Clearing Factor Optimization

The pulsed excitation process rapidly heats the gas in the cavity. The heated gas volume subsequently expands, sending pressure waves out into the flow loop. The heated and expanded gas volume must be moved sufficiently downstream of the cavity region prior to the succeeding pulse. The flow Mach number of an efficient closed-cycle laser is chosen so that this thermal clearing process is balanced with the pressure wave clearing process to allow the maximum pulse repetition frequency (prf). The clearing factor is defined as the ratio of the cavity flow velocity to the product of the prf and the cavity flow length. Since circulator power varies as the cube of the cavity Mach number for a given loop geometry, a low clearing factor is essential for efficient operation.

The minimum clearing factor depends on the cavity energy loading, the preionization uniformity, the electrode design, the cavity boundary layer, and the discharge physics. The expansion of hot gas upstream that raises the required clearing factor above a vlaue of 1.0 depends on the energy loading[33] and cavity geometry.[21] The presence of laminar[33] or turbulent[34] boundary layers retards the flow near the walls and raises the minimum clearing factor near 2.0.[35]

Preionization uniformity and electric field uniformity as influenced by electrode design have a strong influence on the minimum clearing factor or maximum prf.[5] Electrode design controls the extent of high electric field regions upstream and downstream, which must be cleared of hot gas to avoid discharge instabilities. For the same electrode width, a larger discharge gap will require a larger clearance ratio because of these field excursions. The combination of hot gas, nonuniform electric fields, and unfocused preionization can result in discharge instabilities downstream of the cavity region. A lower clearing factor should be possible if the preionization is well confined into the discharge volume.

The discharge physics also control the minimum clearing factor.[19] Experimental evidence indicates that different clearing factors are needed for excimer laser mixtures than for CO_2 laser mixtures in the same flow geometry because of differences in the physical processes governing discharge stability.[20]

Various closed-cycle demonstration lasers have operated with clearance ratios as low as 4 in a small (0.8 cm^3) device[16] with poor flow quality and 2.4 in a larger (60 cm^3) device[17] with high-quality flow. Tests and modeling[27] indicate that a clearance ratio of 4 may be required for diffraction-limited operation of a large excimer laser.

Flow System Efficiency

A group at the University of Alabama have developed an iterative numerical procedure to model the steady-state operation of closed-cycle laser flow loops.[1] This model is intended to allow the transient analysis of the closed loop, including detailed models of the heat transfer processes.[36] The steady flow model was experimentally verified in a CO_2 closed-cycle laser.

Mathematical Sciences Northwest (MSNW) has developed a steady-state model of laser closed-flow loop operation that combines conventional component analyses to provide pressure drop values around the flow loop. Analyses of turns, diffusers, and nozzles were taken from wind tunnel and duct design experience, and conventional heat exchanger design techniques were adapted to this application. The experience of many designs indicates that the heat exchanger contributes the largest single component pressure drop in a compact loop design.

We also developed a quasisteady transient flow model that indicated that flow-loop startup transients are dominated by the inertial response of the circulator and its motor and the thermal response of the walls and heat exchangers.

The flow system efficiency may be written

$$\frac{P(\text{out})}{P(\text{flow})} = e_f = \frac{0.02(E_0/p)e_c}{\gamma f D M^2} \tag{2}$$

where Eo/p is the output J/l-atm, e_c the circulator efficiency, and f the cavity clearing factor. This relation is illustrated in Fig. 5 for a closed-loop laser with $\gamma = 5/3$ and a loop pressure drop of one cavity dynamic head. The Mach number is proportional to the product of the aperture width, the prf, and the clearing factor. The efficiency drops rapidly when any of these parameters is increased. The pressure drop coefficient D varies inversely with the square of the flow area expansion ratio. A larger area expansion allows a more efficient flow loop.

Experience has shown that the heat exchanger area expansion ratio to a large extent controls the flow efficiency. The flow-loop volume can be reduced without unacceptable efficiency loss by using a smaller area expansion ratio for the rest of the loop. External flow-loop designs typically have loop to cavity volume ratios near 1000. Flow loops of this type have been designed with a total loop pressure drop on the order of one cavity dynamic head.

For small apertures or low prf, the flow efficiency can be larger than the electrical pulse-forming efficiency, and the laser device efficiency is constrained by the electrical efficiency, as shown in Fig. 6. For larger apertures or prf, the cavity Mach number must be larger and the loop pressure drop

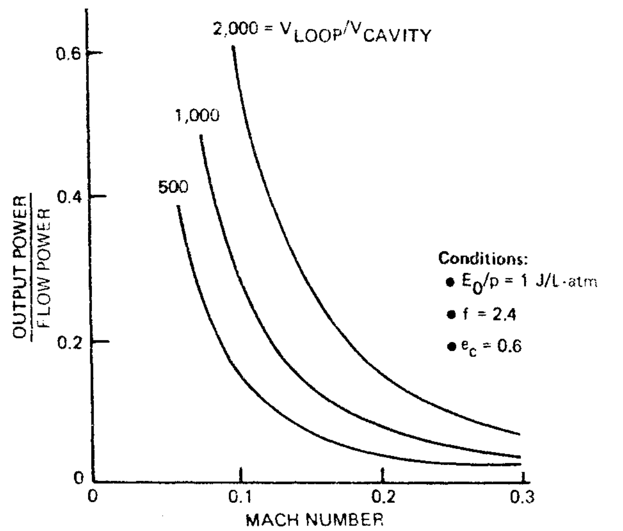

Fig. 5 Flow efficiency and flow system size.

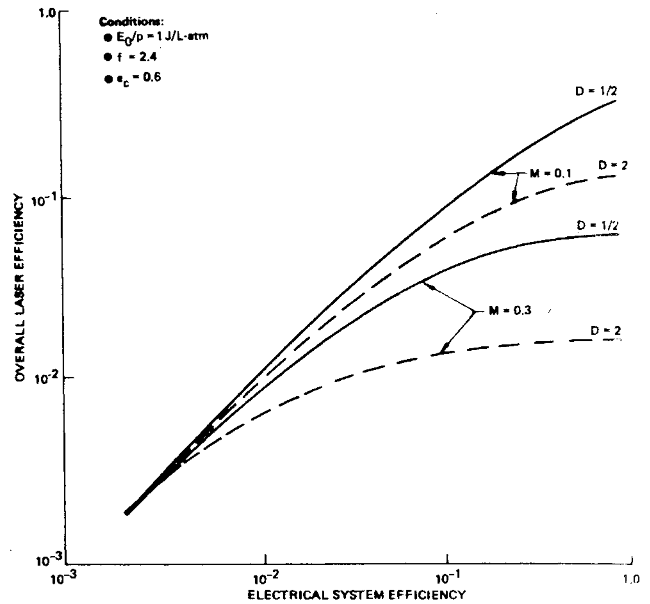

Fig. 6 Laser system efficiency variation with electrical efficiency and flow parameters.

coefficient controls the ultimate laser system efficiency as the electrical efficiency is improved.

III. Pulsed Operation

A small fraction of the input energy appears as pulsed laser output energy. The balance, which is on the order of the entire energy content of the gas flowing into the cavity, rapidly heats the gas in a time period usually less than the gas thermal relaxation time or the cavity acoustic transit time.[37] Unsteady pressure waves that can persist longer than the desired interpulse time are generated by the subsequent adiabatic relaxation of the heated gas volume. The energy in these pressure waves cannot be radiated away as in open-cycle lasers but must be attenuated before returning to the cavity at the time of subsequent pulses. Attenuation of pressure disturbances from levels on the order of 1 atm to levels on the order of 0.0001 atm is typically required in 10 ms or less. Ultimately, this energy is converted to heat and removed at the flow-loop boundaries. The time required to attenuate these pressure disturbances to acceptable levels must be balanced with the time required to clear the cavity region of hot gas to determine the maximum pulse repetition frequency in an efficient pulsed laser design.

Two types of pressure waves can be differentiated by the direction in which they propagate. Longitudinal waves travel in the upstream and downstream directions. Transverse waves travel between the optics and between the electrodes.

Longitudinal Waves

The initial strength of longitudinal pressure waves varies directly with the input energy loading. Typical values of initial wave overpressure lie between 20 percent for pulsed excimer lasers and several hundred percent for pulsed chemical lasers. These pressure disturbances are well above acoustic levels, so that nonlinear analyses are required.

Longitudinal pressure waves have been modeled using one-dimensional, unsteady, nonlinear analyses. To date, the more expensive unsteady two-dimensional analyses have only been used to model certain local phenomena.[25] Originally, the unsteady method of characteristics was used to model longitudinal waves as a logical extension of shock tube analyses.[38] However, the unsteady method of characteristics rapidly becomes too complex when each wave interaction must be followed in multiple pulse situations.

Numerical schemes have been applied more recently to the solution of the one-dimensional unsteady equations for the conservation of mass, momentum, and energy, with source or sink terms to represent interactions with side wall acoustic dampers. Quasisteady models of exchange processes at the perforated side wall have been coupled with conservation equations for mass, momentum, and energy within finite damper backing volumes.

Srivastava and others[39] have developed a second-order MacCormack predictor-corrector numerical algorithm that includes a floating shock fitting scheme to model regions of large property gradients. Some numerical difficulties with the stiffness of the equations have recently been addressed.[29]

Ausherman and others[40] and Hogge and Crow[18] used a finite difference technique with diffusion introduced to assure stability in regions near strong property gradients. A flux-corrected transport algorithm was included to remove the introduced diffusion and no artificial viscosity was used. A dynamic range of four orders of magnitude has been demonstrated using this model.[18]

At MSNW a similar flux-corrected transport algorithm has been used to model complete closed-cycle laser flow loops with area changes, sidewall dampers, heat exchanger, and circulator viscous and heat transfer effects. We found it necessary to model the entire closed-flow loop because long wavelength duct acoustics can dominate the initial shorter wavelength pressure disturbances at later times. This has been found experimentally to be true in open-loop systems as well.[39,41] Calculations at MSNW have shown that persistent long wavelength waves resonate at loop modes because it is easier to attenuate relatively short wavelength cavity-generated disturbances than longer wavelength duct modes using finite volume attenuators. Long wavelength cavity disturbances can be minimized by locating the cavity near a duct node by means of proper flow-loop design and damper placement.

Damper Design

The pressure wave damping system should be designed to maximize the average laser output power by reducing the time required to attenuate pressure waves to an acceptable level without introducing excessive pressure drop and circulator power requirements. These are conflicting requirements because conventional wave damping is normally accomplished by adding viscous drag or by deflecting the flow from the direction of wave propagation. Both of these techniques introduce pressure drop.

Flow-through dampers and orifice plates[42] introduce excessive pressure drop in closed-cycle configurations. Thermal wakes from immersed dampers seriously limit their application upstream of the laser cavity.

A passive damping concept is required that minimally affects the average flow but attenuates the unsteady pressure variations. Acoustic horns have been found to increase wave clearing time if placed between loop components since these horns appear to be poor radiators of nonlinear waves.[29, 39] The transient pressure disturbances have a very wide bandwidth not easily accommodated by an acoustic horn.

A broadband damper is needed to deal effectively with both the short wavelengths associated with steep fronted pulses and with long wavelengths associated with residual duct modes. One should start with a compatible concept proven for nonlinear wave attenuation and extend it to the late time acoustic regime, rather than vice versa. The perforated duct damper design was shown to be very effective in attenuating strong pressure waves in pulsed chemical lasers.[40] Experimental investigations have verified rapid early time attenuation of longitudinal waves, but jets from side wall perforations induced transverse pressure disturbances as high as 0.1%, which persisted for longer than 100 cavity acoustic transit times.[43] When a perforated duct attenuator is used upstream of the laser cavity, these jets contribute to wall-generated disturbances that are convected into the cavity.[27] The solution to this problem lies in the addition of porous wall material to reduce jet size and self-induced noise. Upstream suction can be used to remove the disturbed boundary layers prior to the cavity, as described in Sec. II.

Sidewall dampers have evolved as the attenuators of choice for closed-cycle lasers. Experimentally, the backing depth has been found to influence the wave decay rate.[43] The required backing depth scales with the channel height, and theoretical studies have shown that a depth of twice the channel height, coupled with a wall porosity of 15% offers good performance.[44,29] There is a trade-off among size, flow efficiency, and flow quality since longer, narrower, more effective damper sections introduce more pressure drop and require more circulator power. However, this effect is usually overshadowed by the predominant heat exchanger pressure drop. The damper wall impedance must be decreased gradually in the flow direction near the damper entrance to reduce wave reflections back into the cavity, where they may be trapped.[25,45]

Pressure disturbances that adversely affect optical quality have wavelengths on the order of the optical aperture width. If the wavelength of a pressure disturbance is long enough, the net change in index of refraction across the aperture may be acceptably small or linear enough to be correctable by simple mirror tilt. Srivastava[29] found that sidewall dampers acted in this manner to stretch the wavelength of longitudinal waves.

Another concept involves the scrambling of the pressure wave phase in the optical direction. The optical wave-front distortion then becomes more like a random walk process in

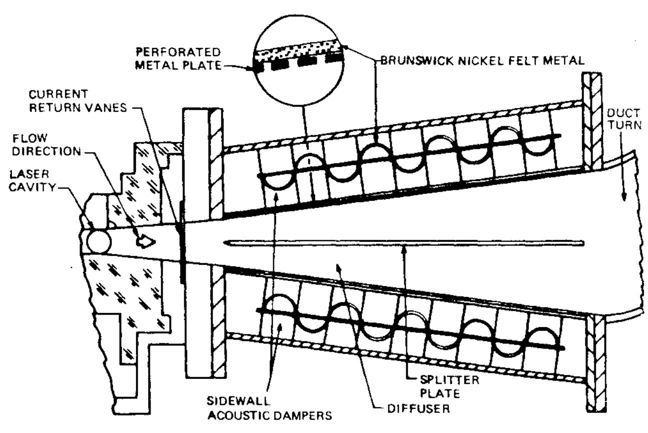

Fig. 7 Detail of sidewall acoustic damper configuration verified experimentally at MSNW.

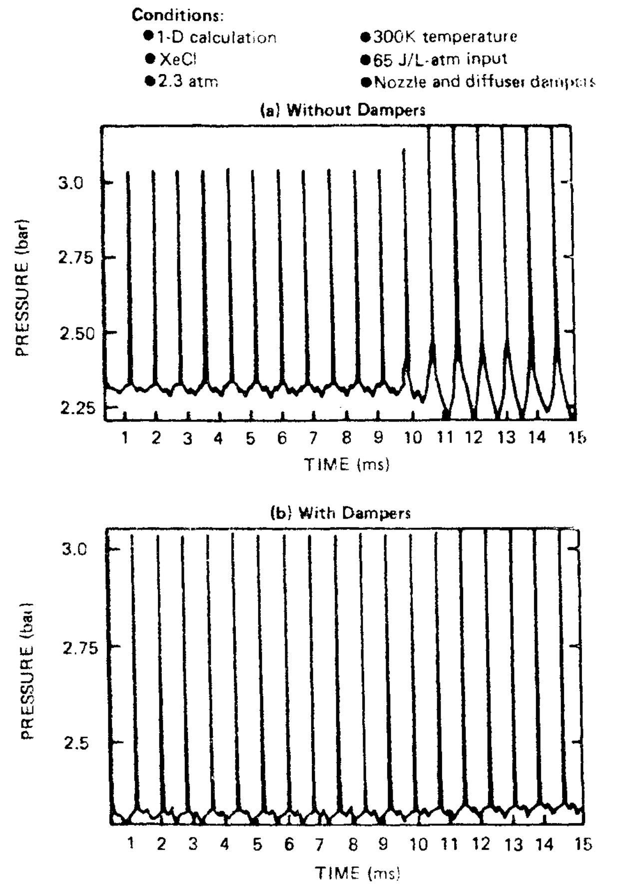

Fig. 8 Calculated effect of sidewall dampers on cavity pressure.

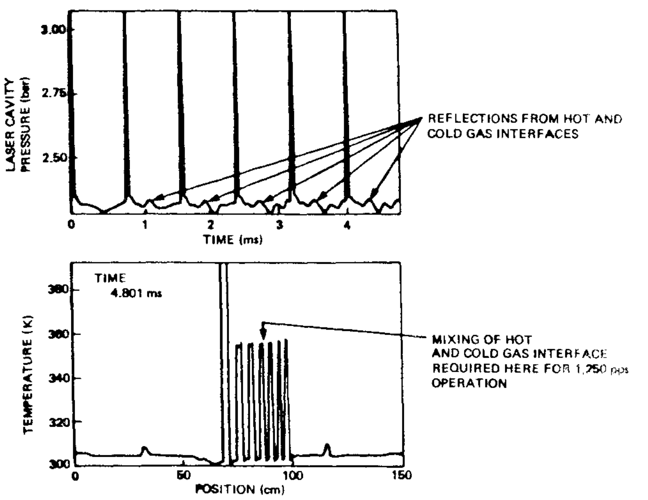

Fig. 9 Pressure disturbances from entropy interfaces.

which the acceptable density nonuniformity increases like the square root of the ratio of optical path length to random structure dimension. The beneficial effects of this phenomenon have been experimentally observed.[21]

Computations and experiments at MSNW have demonstrated the efficacy of locating the sidewall dampers as close to the cavity as possible. We have developed an integrated nozzle/damper and diffuser/damper configuration whose downstream components are shown in Fig. 7. The upstream component combines a sidewall damper with a hodograph nozzle contour in a similar manner. The dampers are tuned over a broad wavelength band using internal felt-metal baffles to attenuate and scramble the pressure disturbances. The depth of the backing volume, which limits the maximum affected wavelength, is constrained by loop geometry. However, we have found that damper placement near the cavity locates a node of long wavelength disturbances near the cavity.

The effect of these dampers in a typical XeCl laser closed-flow loop is shown in Fig. 8. These results were calculated with the MSNW unsteady one-dimensional numerical code described earlier. The flow-loop geometry was similar to that described in Ref. 17. It is apparent that acoustic damping is required to prevent the buildup of pressure fluctuations in the laser cavity. Two-dimensional effects will further disperse pressure disturbances in a compact closed-cycle device.

Flow clearing within 6-8 cavity acoustic transits has been interferometrically measured in a blowdown simulation experiment using similar close-coupled sidewall dampers.[45] Reflections from the hot remnants of previous pulses were not seen in these limited repetitively pulsed tests, however. These reflections can be important, as will now be shown.

Entropy Waves

Entropy waves are density disturbances that result from the interaction of pressure waves with regions of nonisentropic flow. There are two types of entropy waves that occur in closed-cycle laser flow systems.

Upstream Interactions

The passage of a pressure wave can locally alter the entropy production process in the boundary layer on a body such as a current return vane or turning vane immersed in the flow upstream of the cavity. This interaction produces a localized temperature and density fluctuation that convects with the flow from the upstream location of the nonisentropic process through the cavity. The wavelength of this entropy is shorter by a factor of (flow Mach number)$^{-1}$ than the wavelength of the pressure wave that generated it. This process provides a mechanism for otherwise acceptable long wavelength pressure disturbances to produce unacceptable short wavelength density perturbations in the laser cavity. These entropy disturbances are particularly important in open-cycle lasers using upstream orifice plates.[41]

An acoustic damper is usually interposed to attenuate pressure waves before they reach upstream turning vanes or the heat exchanger. There is experimental evidence for entropy waves generated from upstream turbulence management screens that were separated from the cavity by a large area expansion and a sidewall damper section in a closed-cycle laser simulation experiment.[27]

Downstream Interactions

The boundaries of the hot gas volumes produced by the preceding pulses introduce downstream impedance discontinuities that reflect pressure waves back upstream into the cavity region. The results of calculations showing the effects of these downstream intefaces on the operation of a XeCl laser are shown in Fig. 9. The upper figure represents the pressure time history at the center of the cavity from the first to the sixth pulse. The lower figure shows the spatial location of the interfaces just after the seventh pulse. The waves reflected from the first hot gas parcel are clearly evident in the time between the second and third pulses. Examination of these and similar calculations shows that for this particular geometry the reflections from the four preceding hot gas parcels pass through the cavity before a pulse occurs, but the reflection from the fifth preceding parcel lies within the cavity at the time of a pulse. Examination of the spatial density variation in the cavity region showed that with acoustic dampers in place the dominant disturbance to cavity density uniformity was caused by these pressure wave disturbances reflecting from the hot/cold gas interfaces located downstream. Detailed calculations of spatial density variation in the laser cavity using the MSNW one-dimensional numerical code described earlier showed that these disturbances exceeded 0.1% density nonuniformity after the fifth pulse. This level of medium in homogeneity is not good enough for typical excimer laser applications.[18]

Some attenuation of downstream running pressure disturbances before they reach the hot/cold gas interface can be accomplished by dampers placed in the cavity behind the electrodes.[29] These cavity dampers, however, are not compatible with some excitation processes. Also the longitudinal waves do not interact with cavity dampers very effectively.

The reflected pressure disturbances can be reduced by decreasing the reflectivity of the hot/cold gas interfaces. Pressure waves transmitted through these interfaces can be adequately attenuated by the acoustic dampers. Three methods have been proposed to reduce the reflectivity of the hot/cold gas interfaces in closed-cycle lasers.

A heat exchanger can be located immediately downstream of the cavity to reduce the temperature differences in the gas parcels. This component will itself reflect waves back into the cavity, but the advantage is gained by its location near the cavity to allow passage of the reflected wave through the cavity prior to the next pulse. The wave can then be attenuated in an upstream damper section. Calculations using the Whitham method[46] indicate that such a heat exchanger will attenuate the pressure waves as well as decrease the interface reflection. Such a heat exchanger located immediately downstream of the cavity region introduces a pressure drop on the order of 5 to 10 cavity dynamic heads, which severely penalizes the concept for closed-cycle application.

Poseidon Research advocates the placement of a rapid area expansion immediately downstream of the cavity to scramble and mix the hot/cold interfaces.[25] Pressure disturbances reflected from this expansion travel through the cavity and pass into the upstream damper prior to the succeeding pulse. The area expansion attenuates the downstream running wave and acts somewhat like an acoustic diode to attenuate the returned reflection. A two-dimensional numerical model was developed to investigate some aspects of the unsteady process, but the calculations were expensive and modeling the shear layer was difficult. Preliminary experiments using two laser pulses were unable to detect reflections from the hot/cold gas interface to a sensitivity of 0.02% density disturbance.[26] The calculated pressure drop incurred in this expansion is at least 0.5 cavity dynamic head.

An axial mixer concept that is particularly well suited to electric discharge lasers that require a downstream current return grid to minimize discharge circuit inductance has been suggested at MSNW. Even in high-repetition-rate lasers (above 1 kHz) realistic clearance factors place the closest troublesome hot/cold gas interface downstream of the current return location. The current return can be designed to promote enhanced axial mixing of the hot/cold gas interfaces. Axial mixing is accomplished by retarding portions of the flow in viscous layers along internal walls of a honeycomb current return structure. A hot/cold gas interface will be spread axially and sculptured into a complex scalloped profile by wall viscous retardation and centerline fluid acceleration. Enhanced axial mixing will allow turbulent transverse wake mixing to reduce temperature differences decreasing the strength and increasing the wavelength of reflected pressure disturbances.

Pressure waves reflected from the axial mixer structure pass through the cavity prior to the succeeding pulse. Calculations using verified analytical models for boundary-layer growth in tube entrances and for turbulent wake mixing have indicated that such an axial mixer can be designed that would introduce sufficient mixing to attenuate the reflected pressure wave density disturbance to less than 0.2% in a 1250 Hz pulsed XeCl laser. The pressure loss of the combined axial mixer and current return would be approximately 12% of one cavity dynamic head.

This concept looks promising because it uses the existing current return structure to attenuate the hot/cold gas interface reflection in a steady, stable manner with small pressure drop penalty. Very little energy is reflected upstream to be removed in the upstream damper. The concept needs experimental verification in a flowing, repetitively pulsed facility.

Transverse Waves

Pressure waves that propagate in the excitation direction and in the optical direction are generated by spatially nonuniform energy loading and by structural vibrations. Screen or grid electrodes used to protect the foil or to allow uv preionization in an electric discharge laser also introduce discontinuities in energy deposition within the gas, which relax through unsteady pressure waves propagating between electrodes. Inert wall layers to prevent spontaneous ignition introduce similar transverse pressure waves in pulsed chemical lasers. Nonuniformities in initiation, energy deposition, or electric discharge can introduce transverse waves in the laser cavity. Transverse waves generated by foil vibrations have also been measured.[27]

The analysis of these unsteady transverse pressure disturbances requires two-dimensional modeling; however, full, nonlinear two-dimensional modeling is very expensive. Conventional two-dimensional linear acoustics analyses have been used to predict a very slow $t^{-1/2}$ decay of transverse pressure disturbances in the cavity.[25] The analysis by Kulkarney included approximate nonlinear wave techniques to derive a $t^{-4/5}$ decay of transverse pressure disturbances in a parallel hard-wall cavity.[47] These transverse pressure disturbance decay rates are too slow for most high-repetition-rate laser applications.

Sidewall dampers may be placed behind the anode of an electric discharge laser to attenuate transverse waves exponentially.[29,48] Knight has derived the optimum relation for damper backing depth and resistivity to provide a reflection coefficient as low as 20%.[48]

Exponential decay of transverse pressure disturbances may also be obtained by tilting the hard, reflecting sidewalls to "walk" the waves out of the cavity region. An idealized analysis by Knight predicted that effective tilt angles would be large enough to affect flow homogeneity strongly.[48] Measurements by Morris et al.[28] have shown more rapid decay, allowing use of smaller tilt angles. A coupled nozzle and canted cavity area distribution was derived to provide an optically correctable baseline flow density variation across the aperture.[28]

Exponential decay of transverse waves can also be provided by diffraction from the electrode contours themselves. The results of a calculation following repetitive wave reflection from curved electrodes in an XeCl laser with a 6-cm discharge gap and 50 J/1-atm energy input are shown in Fig. 10. The pressure wave driven into the unheated gas behind a screen electrode introduces a large density disturbance that is difficult to attenuate. If a foil is used instead to introduce preionization, the density disturbance introduced by a 25% heating nonuniformity can be attenuated to an acceptable level within the interpulse time by diffraction from a reasonably curved electrode profile. These calculations are presented to indicate the potential for coupling the fluid dynamic and electrical cavity wall contours to provide enhanced transverse wave attenuation.

Kulkarney et al. have recently reported the development of a one-dimensional flux corrected transport analysis with sidewall boundary conditions modified to model two-dimensional acoustic effects in the flow ducts.[49] The code has been verified with shock tube simulations of the decay of transmitted waves and the decay of cavity oscillations for selected conditions. The goal of this model is to combine the proven effectiveness of the one-dimensional flux-corrected numerical analysis of longitudinal pressure waves with an economical, yet sufficient simplified, transverse wave analysis to model adequately the full unsteady flow in pulsed lasers without the expense of complex two-dimensional models. This analysis

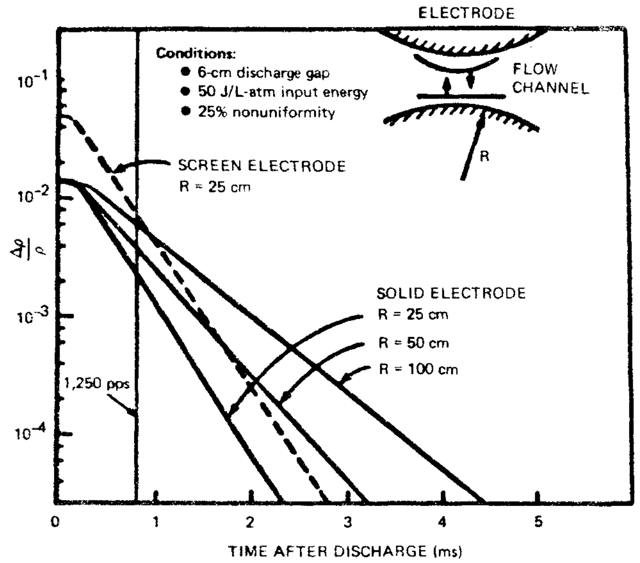

Fig. 10 Diffraction attenuation of transverse waves between curved electrodes.

has not yet been extended to model transverse waves in the cavity.

Transverse pressure disturbances that propagate along the optical axis have little effect on the optical quality of the medium. However, density disturbances associated with these waves must be kept below 1% to avoid discharge instabilities.[20] The presence of these waves has been demonstrated in pressure and interferometer measurements.[27] Sidewall dampers can be placed in the window ducts to attenuate the compression wave that initially travels toward the window. However, it is the expansion wave that travels along the electrode that raises E/n and causes discharge instabilities. The two-dimensional interaction of this transverse expansion wave and the unsteady longitudinal waves is quite complex. At MSNW we have modeled the two-dimensional attenuation of this wave using simple acoustic diffraction, but a more realistic two-dimensional model is needed.

IV. Summary and Issues Requiring Further Resolution

This paper has described the reasons, applications, and requirements for systems providing closed-cycle flow to pulsed gas lasers. Methods that have been developed for the analysis, design, and fabrication of the closed-cycle flow system and its individual components were presented. Flow processes occurring in these systems were considered, together with the techniques used to analyze them and the methods developed to control them.

Although there are many closed-cycle pulsed gas lasers presently in operation, several issues pertinent to the design and operation of closed-cycle flow systems for pulsed gas lasers need further consideration. Resolution of these issues will allow the development of advanced closed-cycle flow systems to provide improved device performance in terms of optical quality, overall efficiency, and system weight, volume, and reliability.

1) Two-dimensional, nonlinear unsteady flow modeling is required to optimize the attenuation of persistent transverse waves that both control the achievement of late time medium homogeneity and affect discharge uniformity. Two-dimensional effects that distort the phase of longitudinal waves in compact flow loops have not been modeled and fully utilized.

2) Development of advanced transverse circulators will allow compact, reliable flow systems that also exhibit high system efficiency. Performance of these circulators in unsteady flow environments must also be investigated.

3) Multipulse experiments are needed to investigate the cumulative entropy wave effects. Experimental verification of the axial mixer is required to develop this promising concept to eliminate a dominant source of cavity medium homogeneity disturbances in a steady, efficient, and compact manner.

4) Analysis of unsteady boundary-layer growth in the upstream acoustic damper is needed to allow the calculation of density disturbances in the cavity and to optimize the upstream boundary-layer suction to provide a more efficient, less complex flow system.

5) More experimental measurements of unsteady pressure disturbances in closed flow systems are necessary to investigate duct resonances and to validate numerical models, allowing more realistic and integrated closed flow loop design.

6) Long run tests are needed to demonstrate system reliability.

7) Advanced electrical, optical, and flow systems must be optimized together to provide an integrated overall laser device design. Improvements in individual system performance can be coordinated with the requirements and characteristics of other systems to optimize the performance of the overall laser device for a specific application.

Note Added in Proof

Recent reports that have become available since this paper was originally written should be included in an up-to-date review of the field. A paper by Forestier et al.[50] was presented at the 5th International Symposium on Gas Flow and Chemical Lasers held in Culham, England, in August 1984. The printed proceedings were not yet available in December 1984. In January 1985 a paper was presented by C. J. Knight[51]. It summarizes and expands upon work done previously at Avco[52] in several areas including baseline flow, longitudinal and transverse wave clearing, sidewall muffler analysis and design, cavity thermal uniformity, upstream sidewall suction, and sidewall entropy layer clearing.

Scaling laws are derived for the attenuation of longitudinal waves in sidewall mufflers showing that the muffler length parameter scales with channel hydraulic diameter times the square root of the relative pulse overpressure divided by the open area ratio. These scaling laws are validated with shock tube data, both new and from the existing literature.

Experiments in a blowdown facility simulating the primary leg of a closed-loop flow system demonstrated longitudinal wave clearing in 15 cavity acoustic transit times. Wavelength stretching was identified as an important process. However, the experiment did not address important closed-cycle longitudinal wave issues.

Transverse wave clearing, which required 28 cavity acoustic transits, was found to be a limiting factor in the restoration of cavity medium homogeneity. Analysis of a "broadbanding" process involving volume absorbers in the sidewall muffler backing volumes predicts an exponential decay of transverse wave pressure disturbances. Diffraction of transverse waves out of the cavity was experimentally found to be the limiting process, and canted cavity sidewalls were advised.

Sidewall entropy layers incorporating gas that has irreversibly entered and returned from the upstream muffler backing volume were not effectively removed by sidewall suction in a pulsed acoustic environment. Elementary scaling relations show that laser system efficiency should not be seriously degraded by the exclusion of these layers from the optically extracted volume.

A flow system conceptual design including close-coupled sidewall mufflers, canted cavity sidewalls, and muffler sidewall suction is described further. Testing and unsteady calculations are recommended to support a more detailed design that includes closed-loop effects.

Acknowledgment

Although I am presently in the Physics Technology organization at the Boeing Aerospace Company, the work reported in this paper was performed while I was with Mathematical Sciences Northwest, Inc. I wish to acknowledge the many contributions of my colleagues at MSNW to the work reported and also the support of Boeing during its preparation and presentation.

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