Supersonic Flow Aerodynamic Windows for High-Power Lasers

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The extraction of a laser beam from the cavity of a high-power laser through a solid window is difficult due to excessive heating of the window material by the absorbed laser flux. A class of devices is discussed and analyzed which uses the momentum of a supersonic jet to support the pressure difference between the laser cavity and the ambient atmosphere and permits the extraction of the laser beam through a nonabsorbing gas medium. The mass flow required for the operation of these devices and the optical quality of the window medium have been investigated as a function of operating conditions and the window design. Measurements of aerodynamic performance and optical quality have been made with a window of this type. This window has operated at a pressure ratio of 10 and measurements show that the beam quality degradation introduced by the window is small, in agreement with theoretical predictions.

Nomenclature

A^* = nozzle throat area
D = aperture size
h = nozzle exit height
h^* = nozzle throat height
h_D = height of exhaust duct
I = degraded farfield intensity
I_0 = undegraded farfield intensity
k = $2\pi/\lambda$
L = propagation length
m = mass flow rate
M = mach number
n = index of refraction
p_0 = stagnation pressure
p_1 = laser cavity static pressure
p_2 = ambient pressure
R = gas constant
T_0 = stagnation temperature
α = extinction coefficient
α_c = see Eq. (4)
α_E = see Eq. (6)
β = Gladstone-Dale constant
γ = ratio of specific heats
δ = angle shown in Fig. 1
λ = wavelength of light
Λ = turbulence integral scale
ρ = gas density
ρ_0 = stagnation density
ρ_s = reference density
σ = shock angle
ϕ = phase angle or expansion angle

Introduction

THE purpose of an aerodynamic window is to permit the extraction of a laser beam from the cavity of a high-power laser through a nonabsorbing gas medium while supporting a pressure difference between the laser cavity and the ambient atmosphere. In a gas dynamic laser,[1] a common example of a high-power CO_2 laser, the laser cavity pressure is typically 0.1 atm and some means must be used to prevent leakage of the ambient atmosphere into the laser cavity. The simplest means of supporting the pressure difference would be with a solid window, however, presently available window materials absorb energy from the laser beam. At high-energy fluxes the heating caused by the absorption of laser energy may distort the window. Beam extraction is also possible by focusing the beam through an output hole small enough that the leakage rate through the hole does not affect the operation of the laser. However, this technique requires the use of long focal length optical elements to prevent air breakdown at the focal point of the high-power laser beam, and has the disadvantage of allowing continuous leakage into the laser cavity. The addition of focusing elements also adds to the complexity of the optical system of the laser.

With a supersonic flow aerodynamic window, the pressure difference between the laser cavity and the ambient atmosphere is supported by centrifugal forces induced by the curvature of a supersonic gas jet. Since the flow is supersonic, turning of the jet occurs across waves, and window designs using both expansion and compression waves have been considered. The flow rate required by these windows is an important measure of their efficiency and depends on the window design and operating conditions. Designs for minimum mass flow have been identified and the mass flow required for various operating conditions has been determined.

The optical quality of the window medium places strong constraints on the types of aerodynamic window designs which can be considered. Density variations in the window medium introduce index of refraction variations which can cause the window to act as a lens with aberrations. Defocusing and also higher-order phase distortions can result which are not easily correctable and cause a reduction in the farfield intensity of the laser beam. The optical quality of the window medium has been investigated theoretically for various window designs and the limitations imposed by optical quality have been identified. For a broad range of design conditions, these results predict that the beam quality degradation introduced by the window should be small.

Two supersonic flow aerodynamic windows have been designed and tested. These windows have aperture sizes of 4 cm and 10 cm and were designed to operate at a pressure ratio of 10. Performance studies were made with the 4-cm window. Aerodynamic performance studies have shown that the design of the window exhaust or diffuser strongly influences the starting characteristics and the operational stability of the window. A design found to give good performance is discussed. Measurements of the optical quality of the window have also been made and confirm that the beam quality degradation is small for the conditions tested.

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Index categories: Supersonic and Hypersonic Flow; Nozzle and Channel Flow; Lasers.

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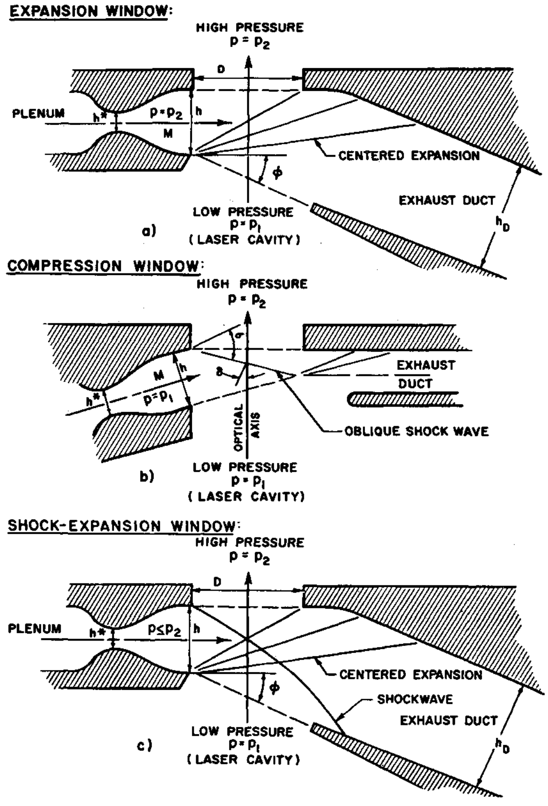

Fig. 1 Design and nomenclature for supersonic flow aerodynamic windows.

Aerodynamic Performance

A supersonic flow aerodynamic window operates by expanding a high-pressure gas to supersonic speeds in a two-dimensional converging-diverging nozzle. The resulting window configuration has a square or rectangular aperture. The pressure difference between the laser cavity and the ambient atmosphere is supported across waves. Either expansion or compression waves may be induced to support the pressure difference as is shown in Fig. 1. In Fig. 1a a simple centered expansion is used in the window. In this configuration the static pressure at the nozzle exit matches the ambient pressure. The flow on the side of the window adjacent to the laser cavity expands to the cavity pressure which is assumed to be below the ambient pressure.

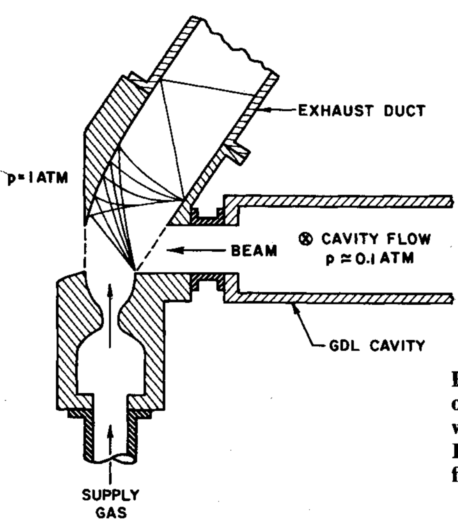

Fig. 2 Application of shock-expansion window to a GDL. Direction of cavity flow is normal to the plane of the figure.

Alternatively, as shown in Fig. 1b, a compression wave can be used to support the pressure difference across the window. In this case the static pressure at the nozzle exit matches the cavity pressure, and the flow on the side of the window adjacent to the ambient atmosphere is compressed to atmospheric pressure by an oblique shock wave. Clearly, the expansion and compression can also be combined with the flow expanding on the low-pressure side of the jet and being compressed on the high-pressure side as shown in Fig. 1c. The application of a shock-expansion window to a GDL is shown schematically in Fig. 2.

Several important aspects of the aerodynamic performance of these devices must be considered. The basic operation of the windows involves only inviscid aerodynamics. From consideration of the inviscid flow the mass flow required for the operation of the windows can be determined, and designs for minimum mass flow can be identified.

The mass flow required for operation of the supersonic compression window depends on the window size and operating conditions. The geometry of the window is defined in Fig. 1b. The flow rate with sonic flow at the nozzle throat is given by[2]

$$\dot{m} = [2/(\gamma+1)]^{(\gamma+1)/2(\gamma-1)}(\gamma/RT_0)^{1/2} p_0 A^* \tag{1}$$

where γ is the ratio of specific heats, R is the gas constant, p_0 is the stagnation pressure, T_0 the stagnation temperature, and A^* is the nozzle throat area. Referring to Fig. 1b, for a square aperture $A^* = h^*D$ where h^* depends on the aperture size D. The throat height, h^*, for a given aperture size is determined from the geometry of the window by requiring that the shockwave span the window aperture which gives

$$h^*/D = (h^*/h)(h/D) = (h^*/h)\cos\delta/\sin\sigma \tag{2}$$

where h^*/h is the area ratio of the nozzle, σ is the shockwave angle, and δ is the angle of incidence of the beam on the shockwave. The area ratio is a function of the desired nozzle exit Mach number, M, and both σ and δ are functions of the Mach number and the pressure ratio across the window. The stagnation pressure, p_0, is determined for a given Mach number by requiring that the static pressure at the nozzle exit equal the pressure p_1. Then

$$\dot{m} = [2/(\gamma+1)]^{(\gamma+1)/2\gamma-1}(\gamma/RT_0)^{1/2} p_2 \alpha_c D^2/(p_2/p_1) \tag{3}$$

where α_c is defined to be

$$\alpha_c = (h^*/h)(h/D)(p_0/p_1) \tag{4}$$

The parameter α_c is a function of Mach number and pressure ratio. At a given pressure ratio, the Mach number may be used as an optimization parameter to minimize the required mass flow. Mass flow is also minimized by making the direction of beam propagation normal to the shockwave. For $\gamma = 1.4$, α_c is plotted as a function of Mach number in Fig. 3. Also shown is the lower limit of Mach number which allows the pressure ratio across the window to be supported by an attached oblique shockwave. It can be seen that mass flow is minimized by operating

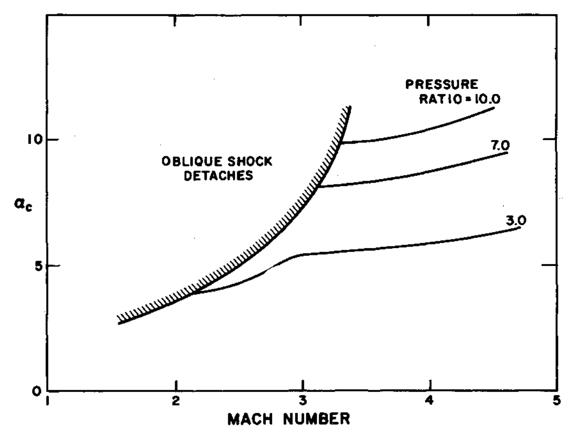

Fig. 3 Variation of the parameter α_c with Mach number.

at the lowest Mach number above detachment at a given pressure ratio. The required flow rate for air with $T_0 = 300°K$ determined from Eq. (3) is plotted in Fig. 4 as a funtion of D for $p_2 = 1$ atm.

The mass flow required for the operation of supersonic expansion window can be determined in a similar manner. Beginning from Eq. (1), the nomenclature in Fig. 1a is used. The window aperture, D, is defined by the intersection of the leading wave with the jet boundary and

$$h/D = (M^2-1)^{-1/2} \tag{5}$$

where M is again the nozzle exit Mach number. With

$$\alpha_E = (h^*/h)(h/D)(p_0/p_2) \tag{6}$$

the required mass flow is given by

$$\dot{m} = [2/(\gamma+1)]^{(\gamma+1)/2(\gamma-1)}(\gamma/RT_0)^{1/2}p_2\alpha_E D^2 \tag{7}$$

The coefficient α_E is a function of only the nozzle exit Mach number, M, and γ and is plotted in Fig. 5 for $\gamma = 1.4$. For a given window size and pressure p_2, the minimum mass flow occurs for $M \simeq 1.8$ and is independent of the window pressure ratio. For $M \lesssim 1.8$, α_E increases because the Mach angle is increasing faster than the stagnation pressure required decreases. For $M \gtrsim 1.8$ the reverse is true. The flow rates required for operation of this window with air at $T_0 = 300°K$ are given as a function of window diameter in Fig. 6 for $p_2 = 1$ atm. Comparison of the results of Fig. 4 and Fig. 6 show that for equal aperture size and pressure p_2 the supersonic compression window requires a flow rate approximately one-third of that for the expansion window.

For a shock-expansion window the pressure rise across the shockwave decreases the required pressure at the nozzle exit. The pressure reduction decreases the mass flow required inversely with the shockwave pressure ratio while the window aperture defined as for the expansion window changes only slightly. The mass flow required for the shock-expansion window with $p_2 = 1$ atm and a shockwave pressure ratio of 1.5 is about two-thirds that of the expansion window as shown in Fig. 6. To minimize mass flow the window should clearly be operated with the largest possible shockwave strength. Equation (7) also shows that the flow rate is reduced by increasing the stagnation temperature or by decreasing the molecular weight of the gas used in the window.

Although the basic operation of these windows depends only on the inviscid flow, the presence of boundary layers can significantly affect the window operation. In the expansion window favorable pressure gradients are maintained at the nozzle exit and consequently no boundary-layer separation should occur. The compression window, however, operates with unfavorable pressure gradients at the shockwave and some method of boundary-layer control will be required to prevent boundary-layer separation upstream of the strong oblique shockwave.

Experimental studies of shockwave induced separation of a flat plate turbulent boundary over a range of flow conditions are reported in Ref. 3. These results show that the pressure rise to induce separation is both Reynolds number and Mach number dependent. The boundary layer along the nozzle wall develops in a favorable pressure gradient and so has a smaller momentum defect than a flat-plate boundary layer at the same Reynolds number. Therefore, measurements for a flat-plate boundary layer can be expected to underestimate the pressure rise to cause separation of the nozzle boundary layers. These results should, however, provide an estimate of the importance of boundary-layer separation in limiting the compression window performance. For a 4-cm window with $p_2 = 1$ atm and $M = 3$, the results of Ref. 3 predict separation at a shockwave pressure ratio of about 3. Higher shockwave pressure ratios are possible for larger values of M, however, this requires higher mass flow for the compression window operation. Some technique of boundary-layer control, such as bleeding off the boundary layer through a slot or porous wall insert, could be used to achieve maximum efficiency for a window utilizing a strong shockwave.

Details of the interaction between the window flow and gas

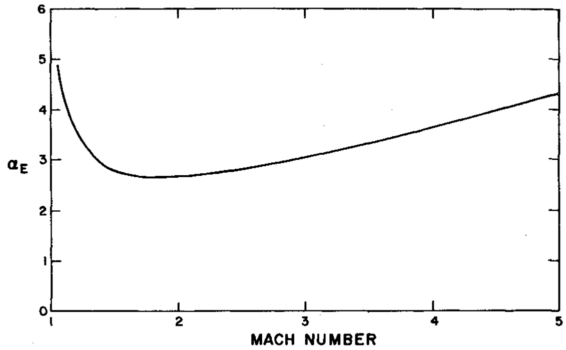

Fig. 5 Variation of the parameter α_E with Mach number.

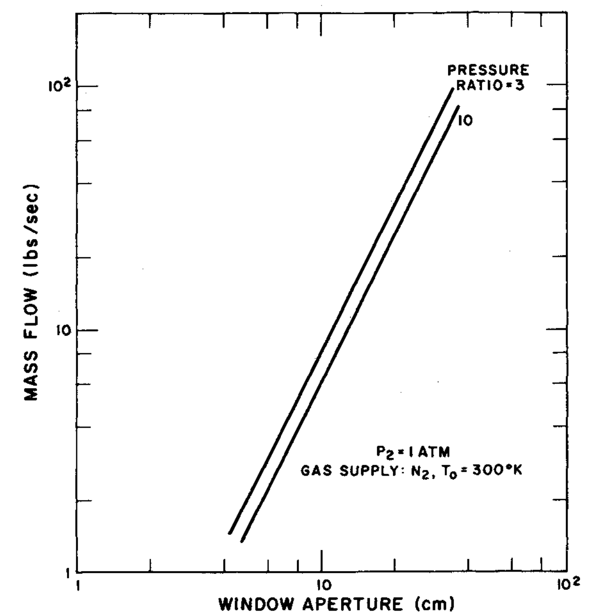

Fig. 4 Mass flow required for compression window operation.

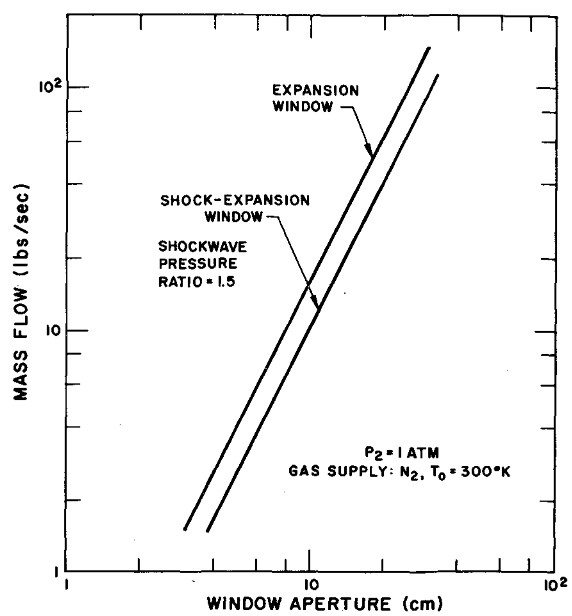

Fig. 6 Mass flow required for expansion window operation.

in the laser cavity must be considered for a particular application. The most important matching condition is that of equal pressure in the window and the laser cavity. With the pressures matched only viscous entrainment will allow mass transfer in the duct between the window and the laser cavity. For application to a GDL in particular, a region of recirculating flow may exist in the duct. If high stagnation temperature laser gas is allowed to enter the recirculation region, large density gradients may result with consequent degradation of the laser beam quality. This can be avoided by designing the window to operate at a slightly higher pressure than the cavity therefore allowing small but continuous ingestion of window gas into the laser. In cases where even a small ingestion rate is intolerable, as in closed cycle devices where the window gas may contaminate the laser flow, the window may be adjusted to act as an ejector pump.

Optical Performance

The optical quality of the window is determined by the index of refraction distribution of the medium in the window aperture. The index of refraction distribution is related to the density field by[4]

$$n = 1+\beta(\rho/\rho_s) \tag{8}$$

where β is the Gladstone-Dale constant and ρ_s is a reference density at standard temperature and pressure. A standard measure of beam quality is peak farfield intensity which depends on the phase distribution of the beam at the output aperture. The peak farfield intensity I, measured relative to the peak farfield intensity for uniform phase is given by[5]

$$\frac{I}{I_0} = \left|\frac{1}{A}\int_A e^{i\Delta\phi}\,dA\right|^2 \tag{9}$$

where A is the aperture area, $\Delta\phi$ is the variation of phase across the output aperture, and the intensity is assumed to be uniform over the output aperture. For small phase variations, Eq. (9) can be written in the approximate form

$$\Delta I/I_0 \simeq \langle\Delta\phi\rangle^2 \tag{10}$$

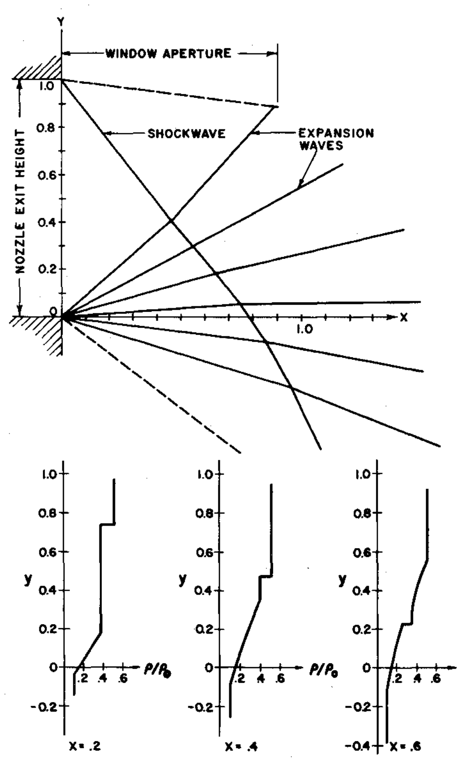

Fig. 7 Wave structure and density field in shock-expansion window aperture.

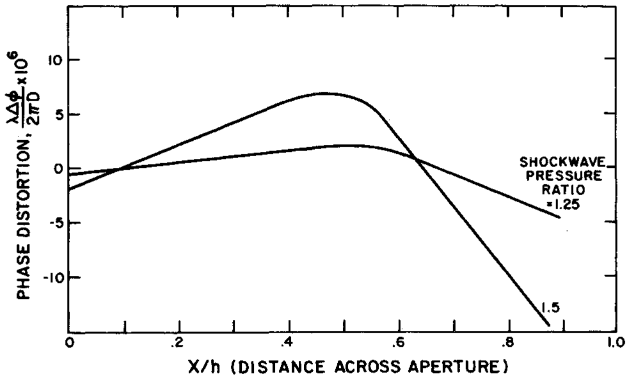

Fig. 8 Nondimensional phase variation across the output aperture.

where ΔI is the farfield intensity degradation and $\langle\Delta\phi\rangle$ is the root mean square phase variation. The linear part of the phase distortion representing beam steering is assumed to be zero in this equation. This component of the phase distortion can be removed by subtracting from the phase variation a linear component which minimizes the resulting root mean square phase variation. For an input beam of uniform phase, the phase distribution at the output aperture according to geometrical optics is given by

$$\Delta\phi = \frac{2\pi\beta}{\lambda}\int\frac{\Delta\rho}{\rho_s}\,ds \tag{11}$$

where the integral is taken along rays of the beam through the density field in the window. In this equation λ is the wavelength of the radiation and Δ signifies differences relative to an arbitrarily chosen reference ray. As the beam traverses the window the deflection of rays due to refraction will be small and to a good approximation the rays remain straight and parallel in traversing the window.

The compression and expansion windows which operate with a single wave cause only a linear variation of the phase across the output aperture which corresponds to steering of the beam and does not represent a degradation of farfield intensity. This can be easily understood by noting that in these windows constant density or index of refraction regions are wedge shaped and act like prisms. The compression window steering can be calculated by adding together the effect of each prism through which the beam propagates. Calculation of the expansion window steering is essentially the same but involves the addition of infinitesimal prisms for the continuous variation of density in the centered expansion.

In the shock expansion window two waves interact in the window aperture and a nonlinear distortion results. The magnitude of this distortion limits the relative wave strengths with which the window can be operated. To calculate the phase distortion from Eq. (11) detailed density distributions in the window aperture must be known. These have been determined numerically using the method of characteristics[2] for obtaining solutions of the interaction of the compression and expansion waves. Typical results for the wave structure and density field are given in Fig. 7 where ρ_0 is the upstream stagnation density and $M = 1.5$. The phase distortion is then calculated by numerical integration of Eq. (11).

The calculated phase distortion in the nondimensional form $\Delta\varphi\lambda/2\pi D$ for a shock-expansion window operating with air at an over-all pressure ratio, p_2/p_1, of 10 is plotted in Fig. 8 for two shockwave pressure ratios with $M = 1.5$, $p_2 = 1$ atm and $T_0 = 300°$K. For each shockwave pressure ratio the linear distortion representing beam steering has been removed. The distortion is linear in the region upstream of the wave interaction as expected. The farfield intensity degradation calculated using these results is plotted in Fig. 9 as a function of shockwave pressure ratio for two window aperture sizes and for $\lambda = 10\mu$. These results indicate that for a farfield intensity degradation less

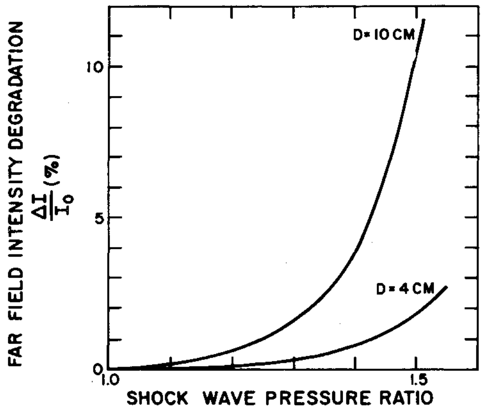

Fig. 9 Farfield intensity degradation as a function of shockwave pressure ratio for a beam of uniform intensity at the output aperture.

than 5%, the shockwave pressure ratio must be less than about 1.4 for a 10-cm aperture. A significantly larger shockwave pressure ratio can be allowed for smaller apertures. The results of Fig. 9 indicate a monatonic degradation of farfield intensity with shockwave pressure ratio. In the limit of the pure compression window, this degradation must again approach zero. Therefore, the extensions of the curves in Fig. 9 should show maxima at larger values of the shockwave pressure ratio.

These results are for operation of the window with nitrogen or air at a stagnation temperature of 300°K with a uniform intensity distribution at the output aperture. The phase distortion varies inversely with the stagnation temperature, and so reductions of phase distortion can be achieved by increasing the stagnation temperature. The phase distortion can also be reduced by operating the window with a gas having lower index of refraction, such as helium. At shorter wavelengths the degradation increases.

The optical performance of the window can also be degraded by index refraction fluctuations in turbulent shear layers which form along the window apertures. This effect will be most severe in the shear layer on the high-pressure side of the window. An estimate of the magnitude of the degradation can be made using results for homogeneous turbulence. For a field of homogeneous turbulence the reduction of farfield intensity due to scattering of radiation by turbulent index of refraction fluctuations is given by[6]

$$I/I_0 = e^{-\alpha L}$$

where the extinction coefficient, α, is given by

$$\alpha \simeq 2\langle \Delta n \rangle^2 k^2 \Lambda \tag{12}$$

and L is the distance which the beam propagates through the turbulent field. Here Λ is the integral scale of the turbulence, $\langle \Delta n \rangle$ is the rms index of refraction fluctuation, and $k(= 2\pi/\lambda)$ is the wave number of the radiation. Using this extinction coefficient the reduction in peak farfield intensity for $\alpha L \ll 1$ is then

$$\Delta I/I_0 \approx 2\langle \Delta n \rangle^2 k^2 \Lambda L \tag{13}$$

These results for homogeneous turbulence have been applied to the nonhomogeneous shear layer by taking L to be the shear layer thickness and

$$\langle \Delta n \rangle \simeq 0.20\beta\, \Delta\rho/\rho_s \tag{14}$$

where $\Delta\rho$ is the density difference across the shear layer. The shear layer thickness grows linearly along the aperture, and the thickness at the center of an aperture of width D gives $L \simeq 0.1D$. The integral scale of turbulence in the shear layer is about one-tenth the thickness, or $\Lambda \simeq 0.01D$. For air or nitrogen $\beta = 3 \times 10^{-4}$ and an estimate of the degradation is given by

$$\Delta I/I_0 \simeq 3 \times 10^{-10}[(\Delta\rho/\rho_s)D/\lambda]^2 \tag{15}$$

With $D \simeq 10$ cm and $\lambda = 10\mu$, values of $\Delta\rho/\rho_s$ near one can be tolerated with only a 3% farfield intensity degradation. Therefore, it appears that the turbulent shear layers will not introduce appreciable degradation of a 10μ laser beam for aperture sizes up to 10 cm. However, the degradation at visible wavelengths can be appreciable. While the use of a low molecular weight gas or air at increased stagnation temperature reduces degradation of beam quality due to transmission through the inviscid flow, this results in increased degradation due to increased density difference across the turbulent shear layers.

The amount of energy absorbed by the window medium will depend specifically on the gas with which the window operates and the wavelength of the radiation. For the case of most interest, $\lambda = 10.6\mu$ with air or nitrogen in the window, absorption will be negligible. In air the principal absorbers of 10.6μ radiation are CO_2 and water vapor which have a combined absorption coefficient less than 10^{-5} cm^{-1} for typical temperatures, pressures, and water vapor concentrations in the window aperture.[7] For a typical path length through the window of 10 cm, less than 0.01% of the power in the laser beam will be absorbed.

Design and Testing of Shock-Expansion Window

A shock-expansion window has been designed to operate at a pressure ratio of approximately 10 and windows with aperture sizes of 4 cm and 10 cm have been built. Combined aerodynamic and optical testing reported here was performed only with the 4 cm window. The expansion angle of the window, ϕ shown in Fig. 1c was 37° corresponding to an inviscid expansion pressure ratio of 10. The nozzle was designed with an area ratio of 1.2 and was contoured to produce a uniform flow at a Mach number of 1.56 at the nozzle exit neglecting viscous effects. When operating as a pure expansion window with a nozzle exit pressure of 1 atm, the stagnation pressure in the window plenum is 4 atm. The 4 cm window is shown in Fig. 10.

Aerodynamic testing was performed with the low-pressure side of the window sealed to form a closed cavity and the high-pressure side exposed to the ambient atmosphere. Pressures were measured in the window plenum, at the nozzle exit, and in the low-pressure cavity. Oil or vacuum grease on the window sidewalls was used as a boundary-layer flow visualization technique. The use of schlieren or interferometric measurements of the flow in the window was also considered; however, the previous relatively simple diagnostics have been sufficient to obtain a reasonable understanding of the window operation.

The aerodynamic testing has shown that the design of the exhaust duct is of great importance to the window performance. Consequently a large part of the aerodynamic testing has dealt with the effect of variations in this aspect of the design. A

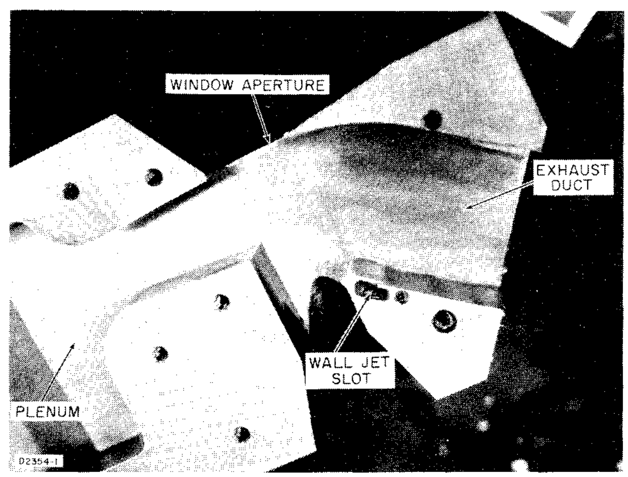

Fig. 10 Photograph of 4 cm aperture aerodynamic window.

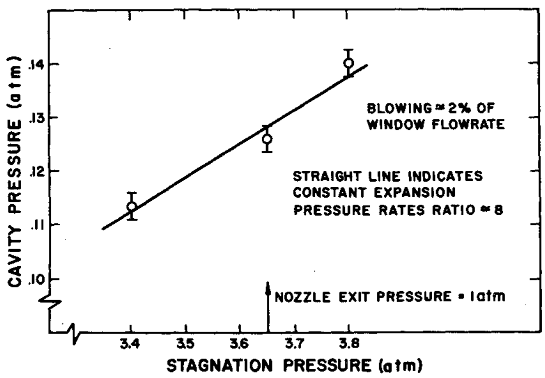

Fig. 11 Pumping pressure as a function of window plenum pressure.

major objective has been to obtain desirable starting characteristics and stable steady-state operation.

The parameter of primary importance in determining the exhaust duct performance is the area ratio between the exhaust duct and the nozzle exit, h_D/h. (See Fig. 1.) Testing has shown that when operating the window as a freejet with no outer wall on the exhaust section or more generally for $h_D/h \gtrsim 2$, a stagnation pressure between two and three times the operating stagnation pressure is required to make the flow initially establish a pressure difference across the window. Furthermore, the flow has been observed to be unstable to externally induced pressure variations in the low-pressure cavity.

For $h_D/h \lesssim 2$, the flow in the exhaust duct entrance is compressed too rapidly giving rise to boundary-layer separation which prevents the flow from completely filling the exhaust duct. This limits the turning angle of the flow through the inviscid expansion and prevents the window from achieving its design pressure ratio. This could be observed clearly in the flow patterns established on the window sidewall. The oil was seen to collect upstream of a strong shockwave standing in the exhaust duct entrance and also in the low-shear region of separated flow on the low-pressure side of the exhaust duct entrance.

This problem was overcome by introducing a sonic wall jet through a slot on the low-pressure side of the exhaust duct entrance as shown in Fig. 10. The jet flow rate was chosen to provide sufficient momentum to prevent boundary-layer separation induced by the shockwave. Gas for the wall jet was supplied from the window plenum, and the size of the slot needed was determined empirically. A wall jet flow rate equal to 2% of the window flow rate was found to be sufficient.

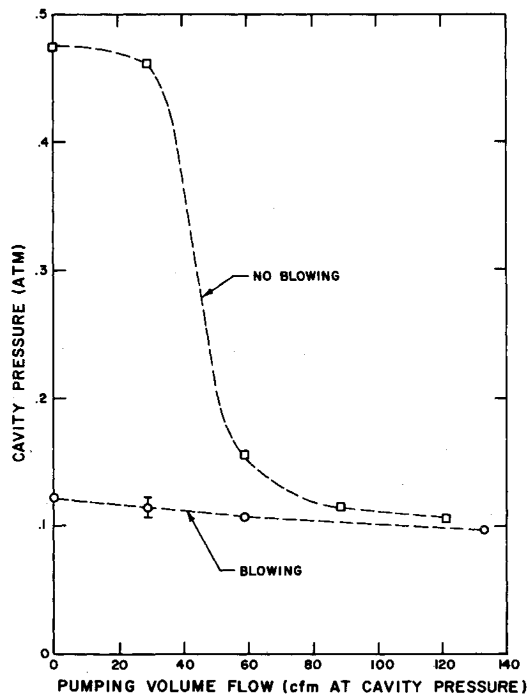

Fig. 12 Cavity pressure as a function of pumping volume flow rate.

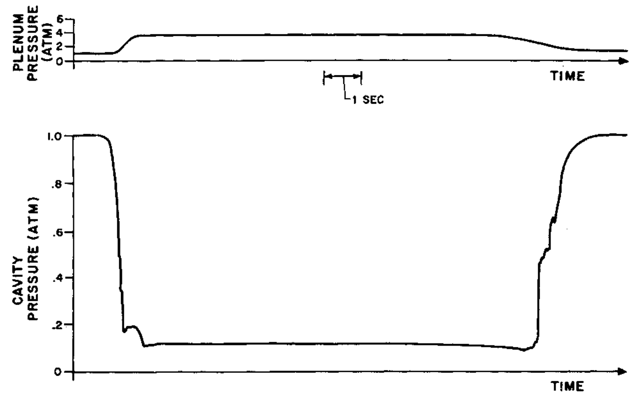

Fig. 13 Plenum and cavity pressures as a function of time during window operation.

The pressure to which the window can pump the low-pressure cavity is plotted in Fig. 11 as a function of the plenum pressure. The data indicate that the pumping pressure is approximately proportional to the plenum pressure. Since the nozzle exit pressure is also proportional to the plenum pressure, the expansion pressure ratio is approximately constant and from the data equal to about 8. The nozzle exit pressure was 1 atm at a plenum pressure of 3.65 atm, and so for isentropic flow the Mach number at the nozzle exit was 1.48. This is slightly below the Mach number based on the geometrical area ratio of the nozzle because the boundary-layer displacement thickness causes a reduction of the effective nozzle area ratio. For an expansion pressure ratio of 8 an effective expansion angle 35° is obtained which is 2° less than the geometric expansion angle. This reduction of expansion angle is consistent with the spreading angle of the dividing streamline for the turbulent shear layer along the low-pressure side of the window which is calculated from the results of Ref. 8 to be 2.5° for incompressible flow.

A set of measurements were made to confirm the effectiveness of the wall jet. In these experiments a 150 cfm vacuum pump was connected to the low-pressure cavity of the 4 cm aperture window, and the pumping volume flow was varied with a metering valve. The window was operated with a plenum pressure of 3 atm giving a shockwave pressure ratio of 1.25. The pressure measured in the low-pressure cavity as a function of pumping volume flow both with and without blowing is shown in Fig. 12.

With no blowing, a pumping volume flow of approximately 80 cfm was required to keep the window fully started. However, with blowing no pumping was required to make the window operate at its design pressure ratio. With wall injection the window can actually operate as an ejector pump. Plenum and cavity pressures as a function of time during a window run are shown in Fig. 13. They demonstrate that this design has given good starting characteristics and stable steady-state operation. Pressure measurements like those of Fig. 13 made with the 10 cm window were essentially identical to those made with the 4 cm window.

The optical quality of the aerodynamic window was determined by measuring the deflection and degradation of a diffraction limited 10.6μ laser beam which was transmitted through the window and focused 5 m away onto an aperture as shown in Fig. 14. The diameter of the aperture was equal to $\frac{2}{3}$ of the diffraction limited focal spot size which was 3 mm. The power transmitted through the aperture is a measure of the focal spot

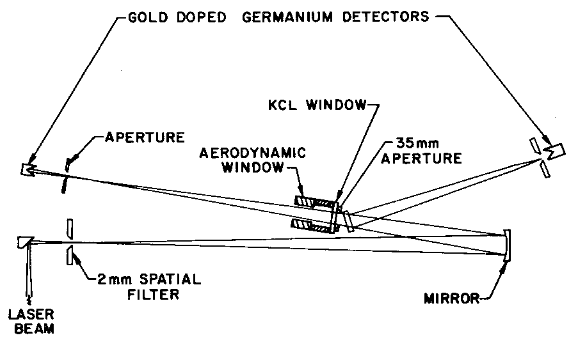

Fig. 14 Optical system for measuring beam quality degradation.

size which varies inversely with the square of the peak intensity within the focal spot. To remove the influence of variations in the power output of the laser source, the measurements were made relative to a reference beam reflected from the main beam before it passed through the window as shown in Fig. 14. Further details of the optical system are shown in this figure. The use of visible light interferometry was considered for measuring the optical quality of the window. This technique is a very sensitive indicator of the transmission quality of the window at 10 cm since, as noted in Eq. (11), the phase distortion produced by density variations in the flow are inversely proportional to the wavelength of the transmitted light. Unfortunately, density variations in the turbulent shear layers refract the light so much that the finite fringe pattern of the interferograms would become indistinguishable. As noted previously, turbulent shear layers should introduce only small variations in farfield intensity of the laser beam, so the interferogram overaccentuates the influence of the turbulence.

With the aerodynamic window not operating the system was balanced, and then with the window operating the aperture position perpendicular to the direction of beam propagation was adjusted to the peak power point and the difference from the balanced condition was measured. The accuracy of the data which could be obtained in this way was limited by atmospheric density fluctuations within the beam path. With the aerodynamic window not operating, the measured power fluctuated by about $\pm 5\%$. Within this accuracy it is possible to say that the degradation induced by the window for shockwave pressure ratios up to 1.35 was at most 5%. Measurements of power made as a function of aperture position in a direction perpendicular to beam propagation are given in Fig. 15 and are indicative of the intensity distribution at the focal point with and without the window operating. The shockwave pressure ratio was 1.35 which is the largest tested. No large change in the intensity distribution could be detected. While these measurements cannot resolve the details of the degradation caused by the window, it is clear that this degradation is small and is in agreement with the magnitude of that predicted theoretically. Beam steering effects at the focal point were 10% or less of the focal aperture diameter. The largest steering observed was 30μ rad with the window operating in its pure expansion mode which should be compared with a calculated steering of 53μ rad.

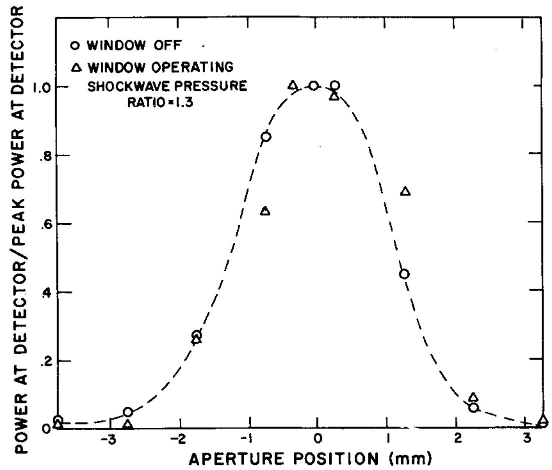

Fig. 15 Intensity distributions obtained by moving scanning aperture through focal point.

Conclusions

Supersonic flow aerodynamic windows appear to be an effective technique for beam extraction from the cavity of a high-power laser. While the windows require high-mass flow, they can effectively support large pressure differences with small beam quality degradation. Several general conclusions about the design of these windows have emerged. The flow rate required for this type of window is minimized by maximizing the compression wavestrength. This, however, will be limited by the occurrence of boundary-layer separation at the nozzle exit unless some technique of boundary-layer control is utilized. To maintain high optical quality in a window operated with two waves, one of the waves must be weak compared to the other, typically 20–25% for a 10μ beam quality degradation of 5% with a window aperture of 10 cm. Turbulent shear layers along the window apertures are not a significant source of beam quality degradation. Further study is required to define the details of the window performance more precisely; however, the results presented here confirm the feasibility of supersonic flow aerodynamic windows. Reference 9 is a recent report containing additional detailed data on the optical performance of supersonic flow aerodynamic windows.

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