Experimental and Computational Investigation of a Gas Laser Pressure Recovery System Diffuser

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14. ABSTRACT
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Experimental and Computational Investigation of a Gas Laser Pressure Recovery System Diffuser

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Abstract. A diffuser, with the purpose of efficiently recovering pressure from a gas laser system, was designed and studied. A diffuser, as part of a pressure recovery system, is used in a gas laser system to transition the laser cavity's low pressure to the ambient pressure outside the device. The diffuser studied here is made up of a constant-area supersonic section and a diverging subsonic section. The diffuser is studied experimentally with pressure measurements and is modeled with 3-D CFD.

INTRODUCTION

Chemical Oxygen Iodine Lasers (COILs) are supersonic flow devices with expansions to pressures less than 10 Torr at Mach numbers of 2 or greater. When the low pressure gas exits the lasing cavity, the region of maximal expansion, the pressure must be recovered to the much higher ambient conditions outside the device. In many cases a passive supersonic diffuser followed by a steam-driven ejector is used to increase the pressure. In a supersonic diffuser, the gas passes through an extended series of oblique shock waves that recover the flow pressure while reducing the flow momentum.[1,2] Increasing the diffuser's efficiency has the benefit of reducing the length and weight of the overall gas laser system. The diffuser designed here uses a series of oblique shock waves followed by a normal shock to accomplish the pressure recovery. Oblique shock waves are preferred because normal pressure losses are higher across normal shock waves; especially at higher Mach numbers.[3] Thus, using a series of oblique shock waves can increase the efficiency of the diffuser.

Diffusers with gas laser applications are studied for optimization towards reduction of the pressure recovery system weight and for mitigating against un-start of the gas laser (where pressure isolation is lost resulting in the adverse pressure gradient inducing boundary layer separation and destabilization of the gas flow).[4,5,6,7] In this study, a diffuser was designed to test on a small-scale test stand, using non-

reacting flows. The gas was delivered to the diffuser with a Mach 2.2 nozzle. Pressure data was taken to evaluate the diffuser efficiency and to determine if the diffuser was increasing the effluent gas pressure while keeping the pressure in the lasing cavity low. Computational Fluid Dynamic (CFD) simulations were performed on this hardware configuration to compare with the experimental results and to enhance the understanding of the interaction of the flow structure and how it influences the operation of the diffuser.

DIFFUSER DESIGN

The diffuser was designed with a constant-area supersonic section and a diverging subsonic section which was manufactured to fit on an already-existing test stand. The experimental results are used to compare and validate CFD data and to assist in larger-scale designs. Figure 1 is a schematic of the diffuser. There are pressure taps located on the top and bottom of the diffuser. There are three taps per row and 16 rows on the top and bottom of the diffuser. Figure 2 gives the dimensions of the diffuser and Fig. 3 shows a picture of the nozzle and diffuser on the test stand. The sidewalls consist of polycarbonate inserts to allow future gas flow imaging.

The primary gas flows, through the nozzle, are 500 mmol/s of helium and 125 mmol/s of oxygen. Nitrogen and helium are injected in the supersonic section of the nozzle, at rates of 133 mmol/s of helium and 16 mmol/s of nitrogen. Nitrogen gas was used in place of iodine to simplify experimentation. The total mass flow is 0.00698 kg/s, with a nozzle exit Mach number of 2.4.
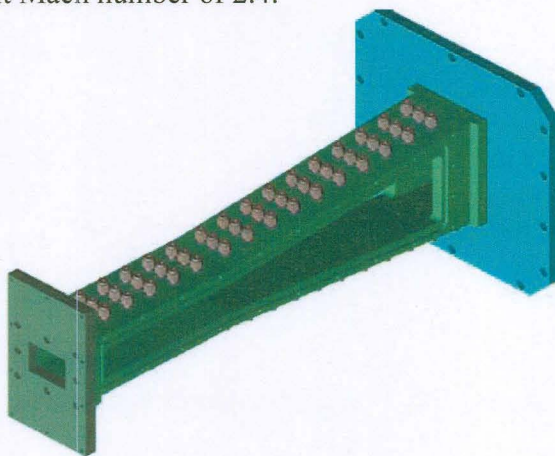
Figure 1. A schematic of the diffuser. The direction of the gas flow is from left to right.
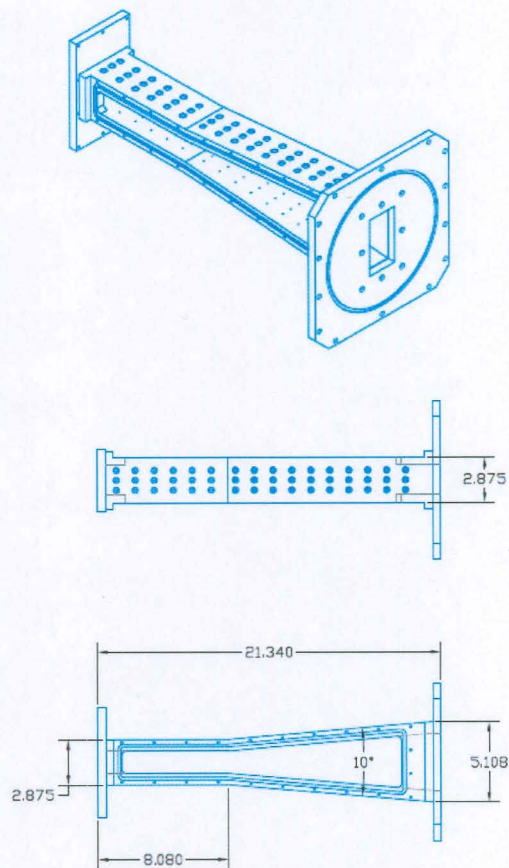
**Figure 2.** Diffuser dimensions. All units are in inches.
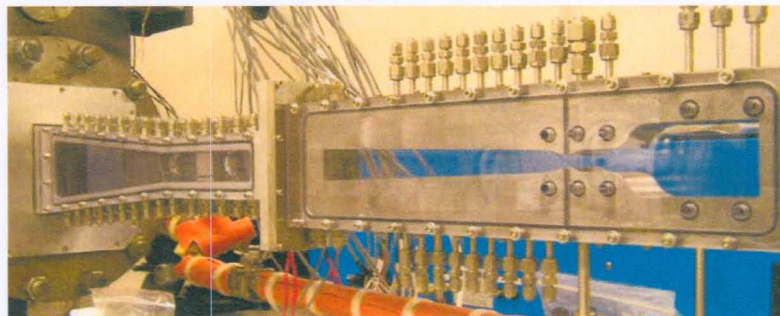
Figure 3. Picture of a nozzle and the diffuser. Gas flow is from right to left.

EXPERIMENTAL RESULTS

The experimental results include pressure measurements from the top and bottom wall pressure taps and from a Pitot tube inserted through one of the polycarbonate walls. The system was designed so that the back pressure increased with time while obtaining the pressure measurements. This was done by using a reduced-sized vacuum

line so that the gas flow would increase the line pressure. This variable back pressure allows the study of the shock wave movement through the diffuser and nozzle. With increasing back pressure, the normal shock moved upstream, toward the nozzle. Static pressure versus downstream distance from the nozzle throat is displayed in Fig. 4. The nozzle plenum is indicated by the negative distance from the nozzle throat, where the plenum pressure is 65 Torr. Along each curve, there is a jump in the static pressure. At a low back pressure, this occurs in the constant-angle portion of the diffuser (which starts at about 535 mm from the throat). This would indicate the location of the normal shock wave. With increasing back pressure the jump in static pressure, caused by the normal shock wave, moves closer to the nozzle throat. Up to a back pressure of 29.5 Torr, the shock wave does not enter the throat of the nozzle. It is essential to the operation of the laser for the shock wave to remain downstream of the lasing cavity (which is from 20 to 200 mm downstream of the nozzle throat).
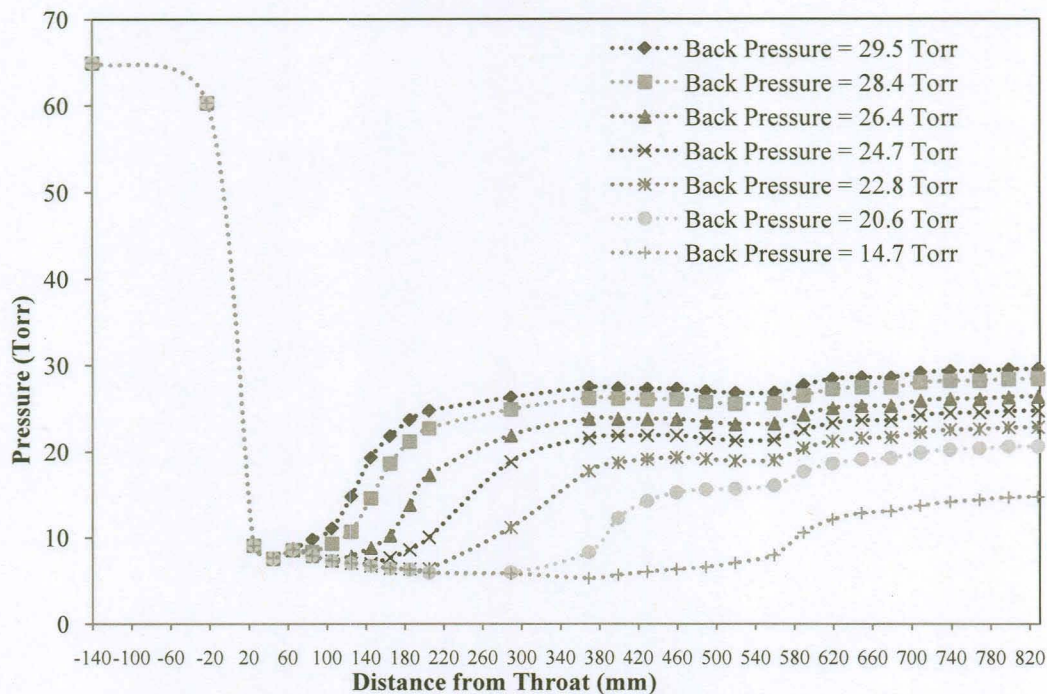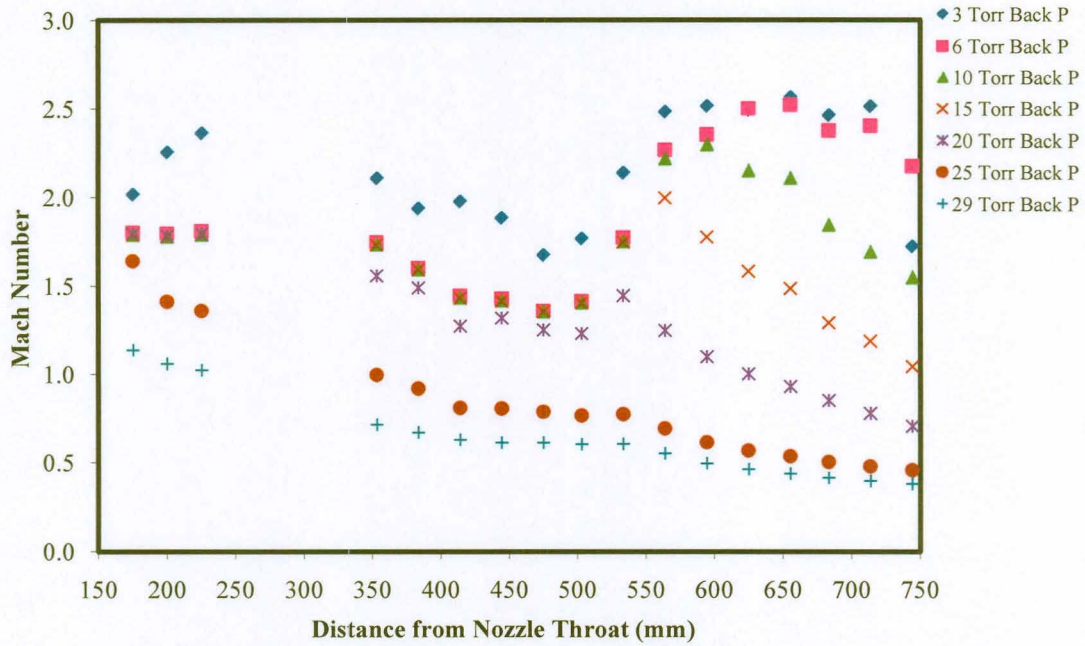

Figure 4. Static pressure versus downstream distance from the nozzle throat, with varying back pressure.

From Pitot tube measurements, the Mach number was measured at the exit of the nozzle and through the length of the diffuser. The Pitot tube measurements were taken with a varying back pressure, as were the static pressure measurements. The Mach number versus downstream distance from the nozzle throat is displayed in Fig. 5. Using the stagnation pressures measured from the Pitot tube, the ratio of the recovered stagnation pressure to the stagnation pressure downstream of a hypothetical normal shock (with zero losses) at the exit of the nozzle is plotted in Fig. 6. This ratio is a diffuser efficiency metric. The diffuser is considered excellent in efficiency if the

efficiency metric is greater than 0.8. The results from Fig. 6 reveal a diffuser that is extremely efficient, even at high back pressures.

Figure 5. Mach number versus downstream distance from the nozzle throat for varying back pressures.
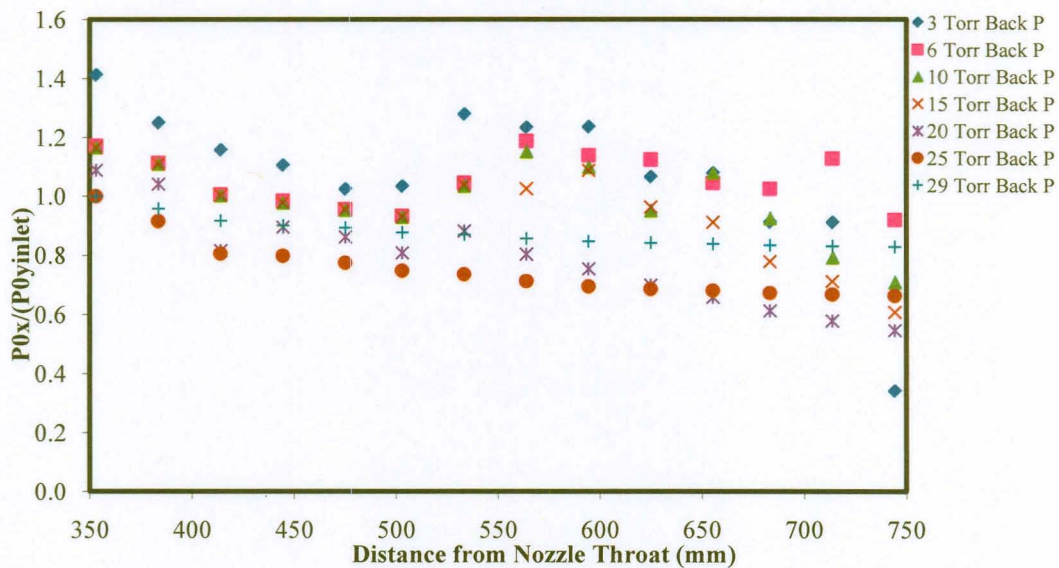
Figure 6. Ratio of local and inlet stagnation pressures versus downstream distance from the nozzle throat for varying back pressures.

COMPUTATIONAL RESULTS

GASP Results

The pressure recovery system for a COIL device transitions the flow exiting the laser to ambient conditions outside of the device. Given the supersonic, reacting flow conditions within the COIL, the flow is first transitioned from supersonic to subsonic conditions through the use of a supersonic diffuser. The supersonic diffuser is a key element in the pressure recovery system, as it must efficiently transition the flow recovering the maximal total pressure possible while maintaining low pressures within the laser cavity just upstream. Thus understanding the basic flow structure is an important first step in understanding how to optimize the supersonic diffuser.

Simulations of representative diffuser hardware were performed to provide greater understanding into the supersonic diffuser flow physics. A GASP 3-D CFD model using reacting, COIL conditions representative of the flow state downstream of the laser resonator was developed. The diffuser inlet conditions are nominally Mach 2.2 with a pressure of 6 Torr and a temperature of 150 K and are modeled as a supersonic inflow in the diffuser simulation. Symmetry plane boundary conditions in the vertical and horizontal direction were used to reduce the size of the computational domain approximating the supersonic diffuser duct and viscous surface boundaries represent the walls. A sharp edged splitter plate initiates an oblique shock pattern in the Mach 2.2 flow that serves to recover the flow. The multi-block computational grid used in these simulations consisted of 21 million cells. The 10-species, 22-reaction COIL kinetics mechanism was used to simulate the gas phase chemical reactions and capture the heat release rate. A time step of $1.0x10^{-8}$ sec was used to advance the simulations in time toward steady-state conditions.

Figure 7 shows the Mach number distribution at the vertical centerline plane with the Mach 2.2 entering the channel and an oblique shock issues from the splitter-plate. The Mach number decreases as the flow passes through the shock, beginning the flow recovery process. As the shock reflects from the sidewall, a recirculation region develops along the sidewall, substantially thickening the boundary layer. The shock reflection initiation of separation in the boundary layer is traced by the flow streamlines and the vortex cores. Additional recirculation regions are seen downstream as the oblique shock reflects back and forth from the sidewall to the splitter plate. These low speed, high residence time regions provide opportunities for the COIL chemical reactions to liberate the energy content within the residual $O_2(^1\Delta)$ remaining after lasing and further thicken the boundary layer, increasing the rate of pressure increase and Mach number decrease within the channel. However, as these conditions are uncontrolled, the effects can be deleterious and lead to increased drag losses within the diffuser. The adverse pressure gradient associated with the shock, as illustrated in Fig. 8 also induces flow separation along the walls orthogonal to the shock. These separation events, visualized by the stream traces within the boundary layer, project boundary layer fluid deep into the freestream. As with the recirculation regions, if not controlled these can be magnified by the presence of the heat release from the chemical reactions to further extend their penetration into the freestream, increasing the pressure prematurely. The combination of premature pressure increases within the

diffuser coupled to flow separation and heat release will eventually lead to diffuser un-start and the development of a strong normal shock that propagates upstream toward the cavity region, an undesirable result.
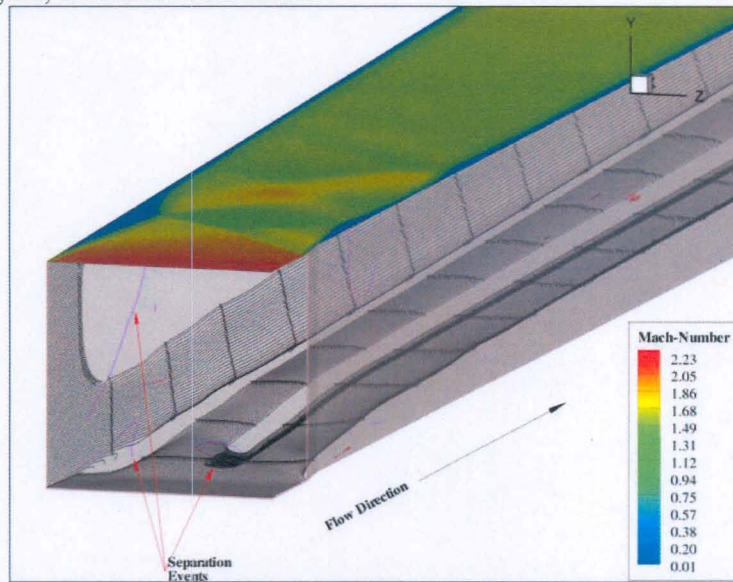
Figure 7. Mach number contours, vortex cores, and streamlines from a 3-D, reacting flow simulation of a COIL supersonic diffuser.
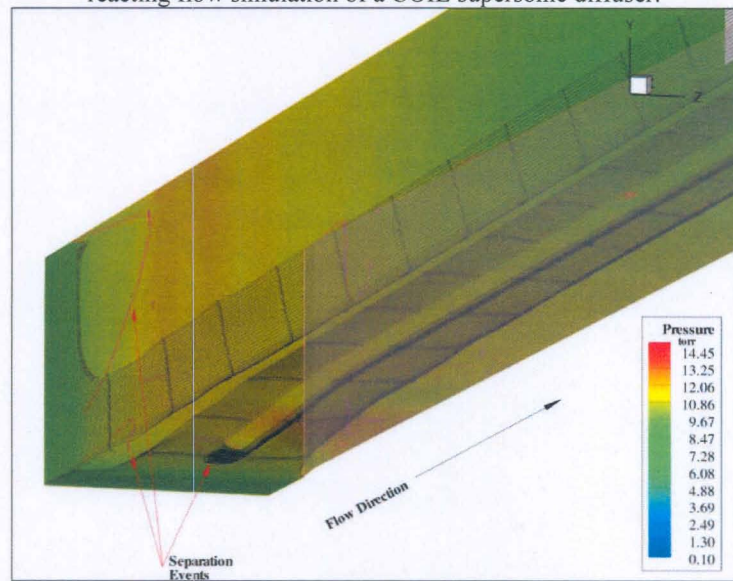

Figure 8. Pressure contours, vortex cores, and streamlines from a 3-D, reacting flow simulation of a COIL supersonic diffuser.

FLUENT Results

With FLUENT, the actual physical base line diffuser is exactly modeled with CFD calculations. The axial pressure distributions between the test and 3-D CFD calculations are compared. FLUENT code with a finite volume formulation was used.

The turbulence model used for these calculations is the k-e model with integration to the wall. It is assumed that wall boundary layer transition starts at 5 in from the throat. The flow calculations were done with the same primary and secondary flows as used in the tests, with one vertical symmetry plane used in the computational domain. The number of cells in the model exceeds 10.5 million even after taking advantage of this symmetry plane, with the smallest cell size being 0.002 in at the wall boundary and 0.005 in at the centerline near the throat and in the supersonic nozzle, and up to 0.015 in at the wall boundary and 0.06 in at the centerline near the subsonic diffuser exit. An isometric view of the computational grid is shown in Fig. 9.
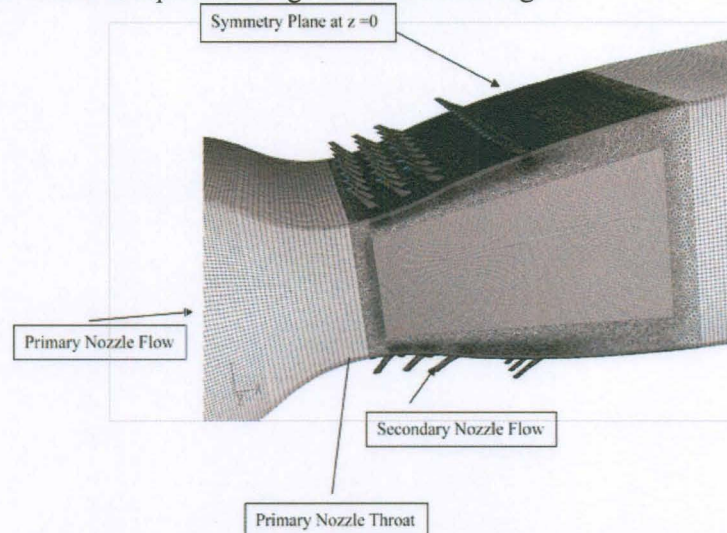
Figure 9. Isometric view of the computational grid for the baseline diffuser with secondary nozzles. (Over 10.5 million cells.)

Comparisons of the computational results to test data are shown in the next three graphs. The purpose was to roughly find the acceptable highest back pressure, i.e. pressure recovery. In Figure 10 the back pressure is chosen to be a low pressure of 10 Torr to establish a baseline pressure in the chosen "lasing cavity" which is a length of about 250 mm or 10 inches (in) in the flow direction. Assuming that the "lasing cavity" starts at 5 in downstream of the throat, it could be 15 in. long, i.e. from 5 in. to 20 in. The calculation starts in the constant area section of the primary nozzle 1.466 in upstream of the throat. The static pressure remains at or below 8 Torr till 25 in. There is an indication in the pressure traces that the calculated boundary layer is a bit more resilient than the actual boundary layer in the test.
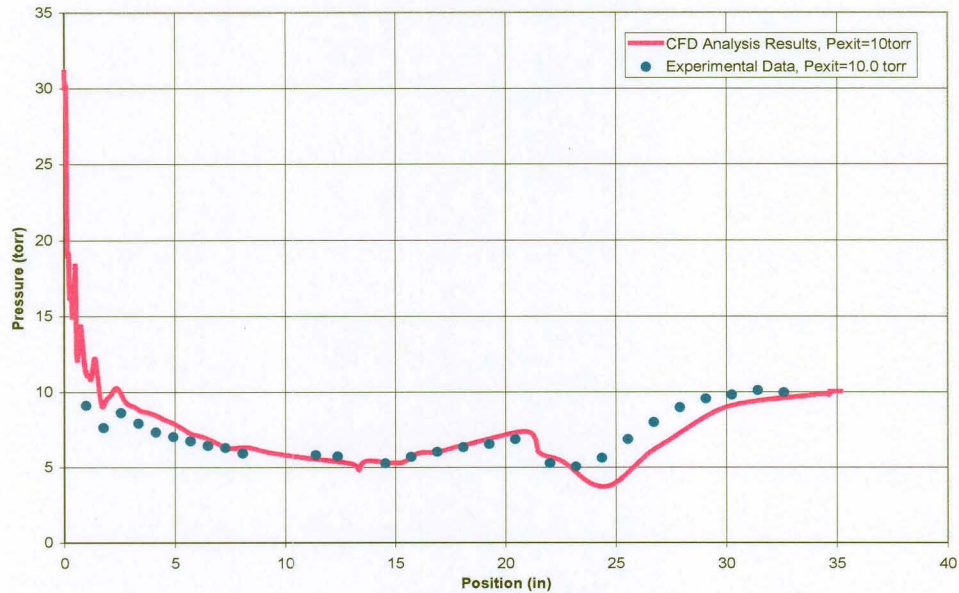
Figure 10. Baseline diffuser static pressure (centerline, top wall) versus streamwise distance from the nozzle throat (10 Torr back pressure).

The second test and CFD calculation case were done for a back pressure of 20 Torr. See Fig. 11. Again, for the CFD calculation, boundary layer transition is assumed to be 5 in from the primary nozzle throat. If the end of the simulated lasing cavity is considered to be at 15 in, 20 Torr is an acceptable pressure recovery. The calculation versus test boundary layer shows that the calculated boundary layer resists the 20 Torr back pressure better that the actual boundary layer. Hence, given the flow conditions, it might be advisable to trip the boundary layers. The naturally occurring vortices which are produced by the secondary nozzle flows interacting with the primary nozzle flows apparently are not sufficient to completely trip the lasing cavity boundary layers.
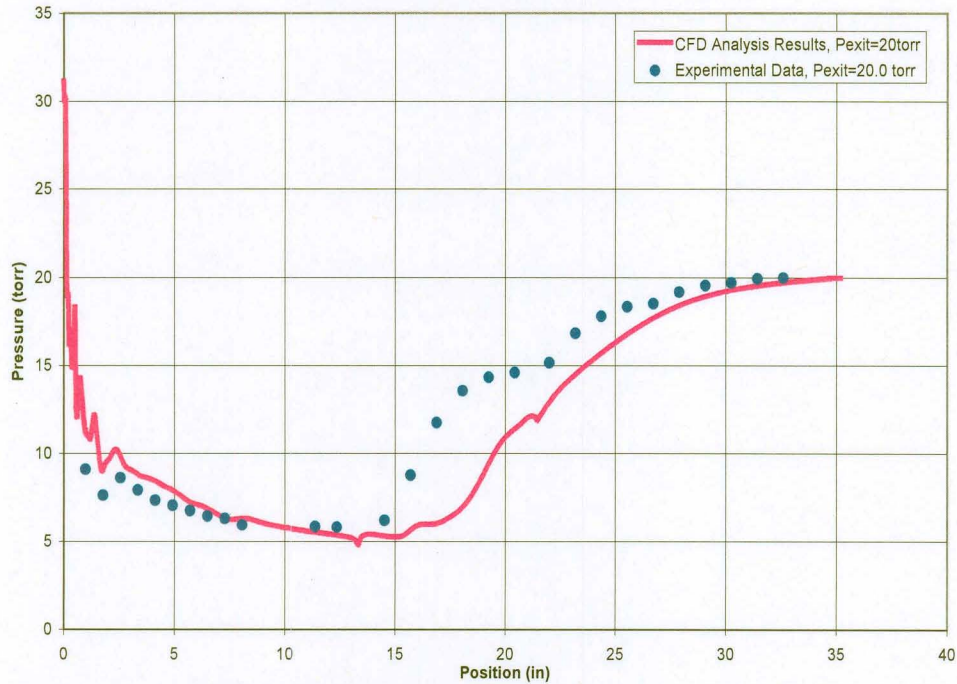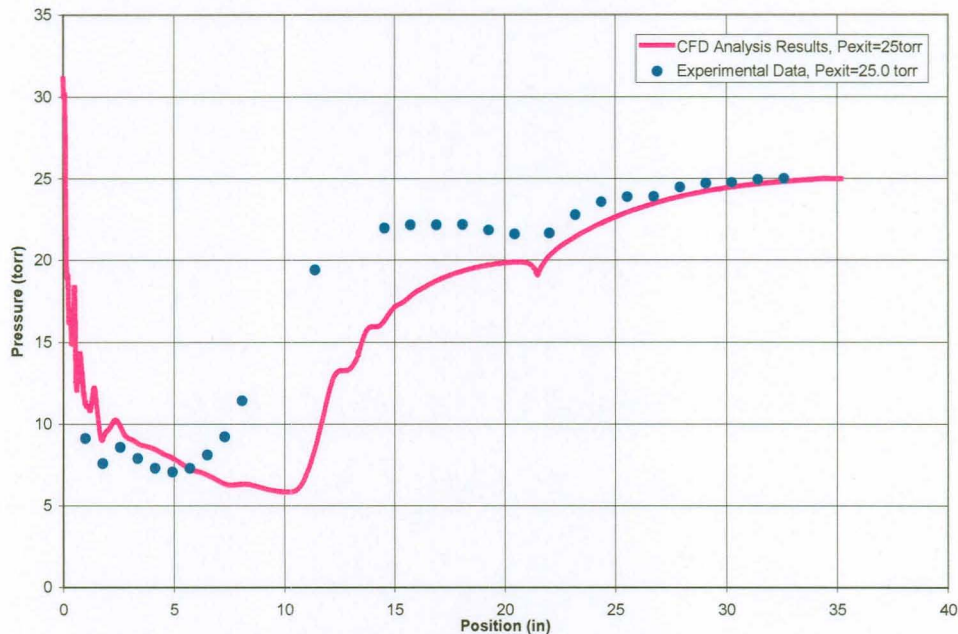
Figure 11. Baseline diffuser static pressure (centerline, top wall) versus streamwise distance from the nozzle throat (20 Torr back pressure).

The third case, Figure 12, where tests and calculations are done for a flow case with 25 Torr back pressure, emphasizes the importance of early boundary layer transition even more so. Of course, there are limits. The calculation results show that early transition alone is not sufficient to allow for a long enough low pressure lasing cavity. Additional work will be done to examine possible more efficient (lower loss) pressure recovery methods.

Figure 12. Baseline diffuser static pressure (centerline, top wall) versus streamwise distance from the nozzle throat (25 Torr back pressure).

CONCLUSION

The results from these tests are encouraging. The pressure measurements reveal a diffuser that efficiently recovers the pressure in system with a back pressure as high as 20 Torr and keeps the gas flow separate in the lasing cavity. The diffuser efficiency metric is greater than 0.8, which is excellent, though the gas delivery system is more uniform and predictable than in an actual COIL device. The tests with the diffuser on our small test stand and the CFD calculations are still preliminary findings. More diffuser designs will be studied, on this test stand and on a larger test stand. The CFD calculations are incomplete at this time. They are being performed to increase the understanding regarding the interaction of the flow structure with the COIL chemical reactions, an important consideration for the end application of the diffusers.

ACKNOWLEDGMENTS

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