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ADVANCED MIXING NOZZLE CONCEPTS FOR COIL

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Abstract

This paper investigates advanced mixing nozzle concepts for the chemical oxygen-iodine laser (COIL) that will significantly improve the chemical efficiency of such systems. It is believed that innovative nozzle design improvements should increase COIL chemical efficiencies. This technology will logically include injection of atomic rather than molecular iodine. The resulting family of advanced nozzles will have major implications for the military programs as well as evolving industrial COIL systems. Research into these concepts will improve chemical efficiencies, reduce gain generator subsystem cost and weight, reduce loading on optical components, and improve pressure recovery. Use of the well calibrated and economical VertiCOIL facility at UIUC will allow a number of advanced nozzle concepts to be implemented and examined in detail.

1. Introduction

The Chemical Oxygen-Iodine Laser (COIL) was developed first by the United States Air Force in 1978 [McDermott, 1978]. Since that initial demonstration COIL technology has undergone numerous improvements [Truesdell, 1992] and chemical efficiencies as high as 27-30% using helium diluent have been demonstrated [Rittenhouse, 1998; Yang, 1997]. Much of the COIL technology development to date has focused on the singlet-oxygen generator (SOG) and the liquid SOG technology has developed to a fairly mature state; major improvements to the aqueous system are less likely to occur, especially in terms of efficiency to weight. However, the basic COIL nozzle design has changed little over the past decade. It is believed that significant COIL system improvements can be made via advanced nozzle concepts as well as possible gaseous energy donor concepts. Improvements in nozzle design are likely to be of considerable benefit to the military programs, in addition to improving the economic viability of commercial/industrial COIL systems that are presently being pursued.

Several gain generator technology developments are needed to allow chemical oxygen-iodine laser (COIL) systems to achieve their full potential as efficient producers of 1.3 μm laser beams. These include: 1) Supersonic mixing nozzle efficiencies; 2) Media and beam quality properties; 3) Pressure recovery potential; and 4) Improvements in the $O_2(^1\Delta)$ generator subsystems. This paper addresses the first issue, innovative improvements in mixing nozzle technologies, but development of a new family of mixing nozzles will also have a direct impact on improvements needed in 2 and 3.

The Department of Defense (DOD), and the Air Force in particular, have several important technology thrusts and development programs which would benefit from the nozzle development efforts proposed herein. The Airborne Laser (ABL) and any follow-on efforts would be impacted from proposed efficiency improvements in order to reduce the volume and weight of the laser gain generator and support systems. Improved intensity distribution on mirrors will directly transform into improved optical quality of output beams. Good pressure recovery is essential for operation at lower altitudes. Any improved laser nozzle must address all these issues.

The Air Force, for example, has taken a great deal of care in characterizing well-known laser nozzle configurations and oxygen generators [Truesdell, 1992; Truesdell, 1996; Kendrick, 1998]. They have developed sophisticated diagnostics and conducted detailed analyses of the nozzle flowfields involved. Their laser performance with helium diluent is well characterized and we consider the design of their nozzle (used in RADICL and VertiCOIL) as our “baseline” for the advanced work suggested herein. UIUC has conducted additional work with nitrogen diluent using VertiCOIL. One of the major outcomes from these studies points to the need to develop a more efficient laser nozzle (or family of nozzles). Other critical technologies include the development of an appropriate optical extraction system, and pressure recovery schemes. This paper directly addresses gain generator efficiency improvements over the baseline. It also addresses the improvements in the media (gain/intensity distributions) for optical loading characterization and pressure recovery potential of each design.

2. Objectives

The primary objective of some of our future studies will be to investigate advanced mixing nozzles for the chemical oxygen-iodine laser that will significantly improve the chemical efficiency of such systems. This objective is split into two major subcategories: the investigation of innovative iodine injection techniques and the investigation of novel ways to inject atomic (rather than molecular) iodine. These two subcategories are linked together because the injection of atomic iodine is likely to influence the optimal position at which the iodine should be injected.

It is believed that the answers to these questions will lead to advanced nozzle design improvements that should increase COIL chemical efficiencies to around 35-40%. Such a substantial performance increase will have major implications for the military ABL (or its follow on program), SBL and GBL programs. Further, COIL is a dual-use technology that is in the early stages of commercialization and these improvements will significantly impact the design and operating costs of industrial COIL systems.

3. Preliminary Studies

To investigate important technology issues related to the COIL nozzles, it is useful to employ the COIL heuristic equation developed by Hon *et al.* [Hon, 1996], which is given by,

$$\eta_{chem} = U_{Cl2}\,(Y_{plen} - Y_{diss} - Y_{th} - Y_{deact})\;\eta_{mix}\;\eta_{geom}\;\eta_{ext}\;\eta_{res} \tag{1}$$

where η_{chem} is the chemical efficiency, U_{Cl2} is the utilization of chlorine in the singlet oxygen generator (SOG), Y_{plen} is the yield in the plenum region just upstream of iodine injection, Y_{diss} is the loss of singlet delta oxygen due to dissociation of the iodine molecules, Y_{th} is the threshold yield representing the minimum $O_2(^1\Delta)$ fraction necessary for positive gain, Y_{deact} is the loss of yield due to deactivation reactions, η_{mix} is the mixing efficiency defined as the ratio of the accessed $O_2(^1\Delta)$ to the total $O_2(^1\Delta)$ in the flow, η_{geom} represents the fraction of the flow interrogated by the resonator, η_{ext} is the optical extraction efficiency, and η_{res} is the flow residence time efficiency. The yield is defined as the ratio of excited $O_2(^1\Delta)$ to total oxygen in the flow. The dissociation loss, the threshold yield, and the deactivation loss due to water are defined more precisely as,

$$Y_{diss} = \frac{N\,\dot{I}_2\,F}{\dot{Cl}_2\,U_{Cl_2}\,\eta_{mix}}\;, \tag{2}$$

$$Y_{th} = \frac{1}{1+1.5\exp(401/T_{cav})}\;, \tag{3}$$

$$Y_{deact} = \frac{\int^{V} K_{deact}\,[I^*]\,[H_2O]\;dV}{\dot{Cl}_2\,U_{Cl_2}\,\eta_{mix}}\;, \tag{4}$$

In Eq. (2), N is the average number of $O_2(^1\Delta)$'s used to dissociate one I_2 molecule, F is the final dissociation fraction of I_2, and $\dot{I}_2$ and $\dot{Cl}_2$ are the iodine and chlorine flow rates, respectively [Hon, 1996]. In Eq. (3), T_{cav} is the laser cavity temperature and the constants are determined from the equilibrium rate of the I atom pumping reaction. In Eq. (4), K_{deact} is the deactivation rate constant equal to $2.1\text{x}10^{-12}$ cm^3/molecule-s [Plummer, 1988].

Three important "hard to control" parameters in these equations are N in Eq. (2), T_{cav} in Eq. (3), and the water concentration $[H_2O]$ in Eq. (4). Advanced nozzle concepts may be able to eliminate or reduce the importance of each of these terms, which are significant loss mechanisms in current COIL technology. For example, the dissociation loss term Y_{diss} can be completely eliminated by injecting atomic, rather than molecular, iodine. The current estimate for N is approximately 5 for a typical COIL using molecular iodine, but the injection of atomic iodine would result in N=0.

For a typical RADICL test, Truesdell *et al.* [Truesdell, 1996] provide the following inputs for the heuristic equation: $U_{Cl2} = 0.86$, $Y_{plen} = 0.60$, $Y_{diss} = 0.10$, $Y_{th} = 0.06$, $\eta_{mix} = 0.90$, $\eta_{ext} = \eta_{med}\,\eta_{opt} = 0.91*0.87 = 0.7917$. Hon *et al.* [Hon, 1996] estimate that $\eta_{geom} = 0.98$ and $\eta_{res} = 0.997$ for typical COIL operating conditions. Y_{deact} was neglected by Hon *et al.* because they considered RotoCOIL conditions typical of only the first few seconds of a test when the BHP is cold and the water vapor concentration was very low. As a preliminary estimate, the integral in Eq. (4) is approximately equal to the average concentrations multiplied by the deactivation rate and the volume from injection to the start of the lasing region. To estimate the effect of water vapor later in a test run, species concentration information was extracted from a Blaze II [Sentman, 1977] computer calculation for a typical RADICL test with helium diluent. The average concentrations are $[I^*] = 2.0\text{x}10^{-9}$ moles/cc and $[H_2O] = 2.9\text{x}10^{-8}$ moles/cc, and the approximate volume from the injection point to the start of the lasing region is 201 cc. Using a Cl_2 flow rate of 0.50 moles/s and $U_{Cl2} = 0.86$, then $Y_{deact} = 0.038$, which is small but significant.

Recent experimental data taken by AFRL [Keating, 1997; Kendrick, 1998] and three-dimensional CFD simulations at UIUC [Madden, 1997] indicate that the water vapor concentration and cavity temperature are coupled together due to water vapor condensation. As water condenses as droplets in the nozzle, the water vapor concentration is reduced while simultaneously heating the flow, which increases T_{cav}. There is a trade-off here; a drop in water vapor concentration reduces the effect of Y_{deact}, Eq. (4), but the increase in temperature enhances the loss associated with Y_{th}, Eq. (3). However, it is unknown where the water condensation takes place; if the condensation takes place during the supersonic expansion (after the iodine injection in the subsonic stream), then Y_{deact} will still have an effect on performance in addition to the increased cavity temperature. The measurements of Keating *et al.* [Keating, 1997] indicate cavity temperatures as high as 220K, which is significantly above the 170K cavity temperature predicted by computational methods. If T_{cav} is 220K, then $Y_{th} = 0.097$.

Table 1 presents a preliminary examination of these issues using the heuristic equation [Hon, 1996]. The case studied is the baseline RADICL condition with helium diluent, 0.50 moles/s of Cl_2, 4:1 diluent ratio, and a titration ratio of 1.7%; there is a substantial amount of reported data for this condition [Helms, 1994; Scott, 1994; Tate, 1995].

Table 1. Estimated effects of different conditions on RADICL performance.

	Nominal	Nominal w/o Water	High Temp w/o Water	High Temp w/ Water	Atomic Iodine Injection	Highly Advanced Nozzle
Conditions	H_2O T_{cav}=170K	No H_2O T_{cav}=170K	No H_20 T_{cav}=220K	H_2O T_{cav}=220K	No Y_{diss}	No Y_{diss} No H_2O T_{cav}=150K η_{mix}=1.0
Heuristic Equation (Chem. Eff./ normalized)	24.1% 1.0	27.9% 1.158	24.2% 1.004	20.4% 0.846	34.1% 1.415	43.7% 1.813

Table 1 shows that the heuristic equation predicts a nominal chemical efficiency of 24.1% for the given RADICL case. When all of the water is removed from the flow, the performance increases by 16% to 27.9% chemical efficiency. However, when the temperature of the cavity flow is increased to 220 K, the chemical efficiency drops back to 24.2% when all the water is removed and as low as 20.4% if the temperature is raised and the water remains in the flow. Recent spectroscopic data by Kendrick et al. [Kendrick, 1998] indicate that most of the water condenses in RADICL and that the cavity flow temperature is around 220 K. It is most likely that the water vapor condenses in the supersonic portion of the nozzle. If this is the case, then the Y_{deact} term could be important because of water vapor present in the flow after the iodine injection point, in addition to the large value of Y_{th} due to a high cavity temperature. These issues suggest a possible nozzle design that enables water condensation upstream of the injection point and at the same time a nozzle that gives a lower temperature in the core flow; what might such a nozzle look like? A nozzle that has a higher Mach number than the nominal Mach 2 design on RotoCOIL, RADICL and VertiCOIL would produce lower cavity temperatures. Thus, a well-designed nozzle concept may inject iodine into the supersonic portion of the nozzle, downstream of the principal water condensation point.

A natural question that arises is, can the water vapor be removed from the flow? Given the current aqueous nature of the SOG technology, water is an inherent fraction of the generator output. Water vapor can be mostly removed by the use of cold traps upstream of the nozzle, but such cold traps tend to increase transport volume and/or flow pressure, which results in a loss of yield by the time the primary flow reaches the nozzle [Truesdell, 1992]. This yield loss is significant and can translate to a performance reduction when cold traps are utilized. However, it may be possible to intentionally design a nozzle that condenses water vapor prior to iodine injection. As mentioned above, the condensation process will add heat to the flow, but a higher Mach number nozzle may allow the cavity temperature to be reduced to the 170 K range. Another approach to reduce water vapor that can be tested is that of pre-cooling the primary helium diluent before injecting it into the generator. This approach was first investigated by the Russians using nitrogen diluent [Zagidullin, 1997]. A Japanese-Russian team [Endo, 1998] later demonstrated a significant laser power output increase of 15% using pre-cooled N_2 diluent.

Figure 1 illustrates the limitations of existing COIL technology as well as the possible improvement from the implementation of a single advancement in nozzle technology, i.e., the injection of atomic rather than molecular iodine.

Discussed above was the possibility of injecting atomic, rather than molecular, iodine. For this situation, N=0 in Eq. (2), and thus Y_{diss} =0. The heuristic equation indicates that this alone could result in a 41.5% performance improvement, up to a chemical efficiency of 34.1%, Table 1. Because of the large potential performance enhancement, the investigation of iodine pre-dissociation schemes is important. Conceptually, the ideal nozzle design appears to be one that injects atomic iodine into a waterless primary flow, provides complete mixing by the end of the optical extraction region, and gives a low cavity temperature of around 150 K. The heuristic equation indicates that such a highly advanced nozzle concept could potentially provide an 81% performance improvement up to a chemical efficiency of 43.7%. Since there are many real-world issues in nozzle design, such an advanced nozzle is not realistically attainable. For example, it is very hard to remove all water vapor or other deactivators from the flow, and complete penetration and mixing are harder to attain when injecting into a high Mach number cross-flow. However, it appears that injection of dissociated iodine into the flow coupled with an advanced nozzle design and a proper injection point relative to the optical extraction region may provide chemical efficiencies above 35%. An improvement of this magnitude will lead to a significant reduction of weight of the ABL and SBL systems, as well as large operating cost savings for a GBL or commercial COIL system.

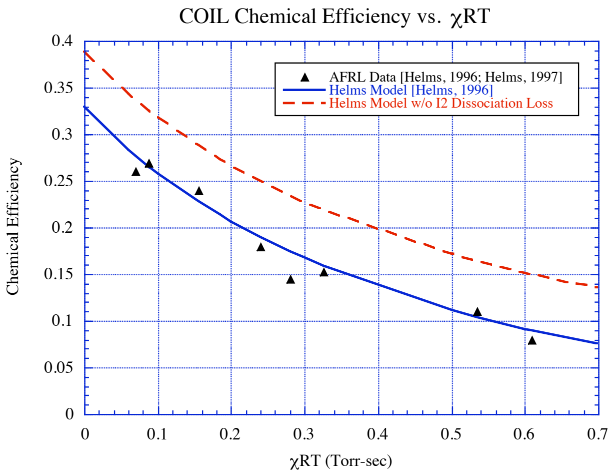

Figure 1. Historical COIL performance and an estimate of the improvement resulting only from the pre-dissociation of the iodine molecules. The illustrated chemical efficiency increase excludes other possible performance enhancements from advanced nozzle technologies. χRT is equivalent to the product of pressure and flow residence time upstream of the nozzle throat.

Preliminary calculations using the Blaze II chemical laser model [Sentman, 1977; Carroll, 1995; Carroll, 1996] support the qualitative conclusions drawn from the heuristic equation. These computations also indicate approximately a 15% performance improvement if water is removed from the flow. Blaze predicts that flow temperature appears to be an issue, but that the effect is not as pronounced as indicated by the heuristic equation; this may be a consequence of the lasing process, which inherently lowers the flow temperature as energy is extracted in the form of photons. Initial calculations with injection of atomic iodine show little change in power, but a significant change in the shape of the gain curve, Fig. 2. This figure clearly illustrates that to efficiently utilize the gain with respect to the optical extraction region (the lasing zone), the injection point needs to be altered when using pre-dissociated iodine. Another Blaze calculation in which the atomic iodine injection point was moved close to the throat (the throat is located 1.1 cm downstream of the nominal injection point) gave an 11% increase in performance over the nominal molecular iodine injection case. Madden *et al*. [Madden, 1998] recently made performance calculations based upon three-dimensional CFD computations using the MINT code. Madden's results indicated that the injection of atomic iodine slightly downstream of the throat would enhance the power output by 10-15% for a realistic set of laser mirrors. Thus, the Blaze calculation for atomic iodine injection near the throat is consistent with Madden's detailed analysis.

These Blaze II results, Fig. 2, and Madden *et al*.'s more detailed computations [Madden, 1998] show that the implementation of an atomic iodine injection scheme also requires a completely redesigned nozzle to properly utilize the gain region. This investigation and nozzle redesign is one of the primary tasks to be performed during these upcoming studies.

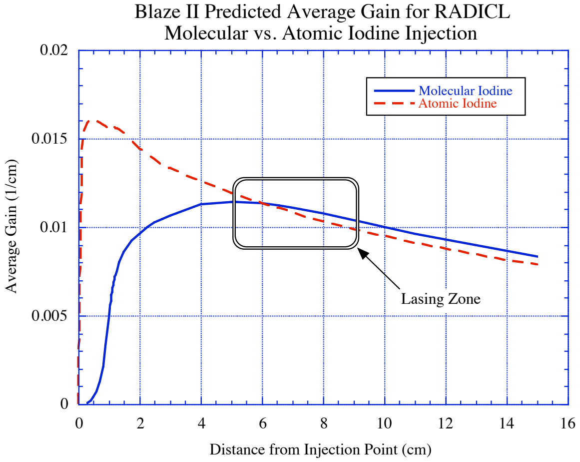

Fig. 2. Comparison of predicted average gain profiles for injection of molecular versus atomic iodine using the Blaze II chemical laser code.

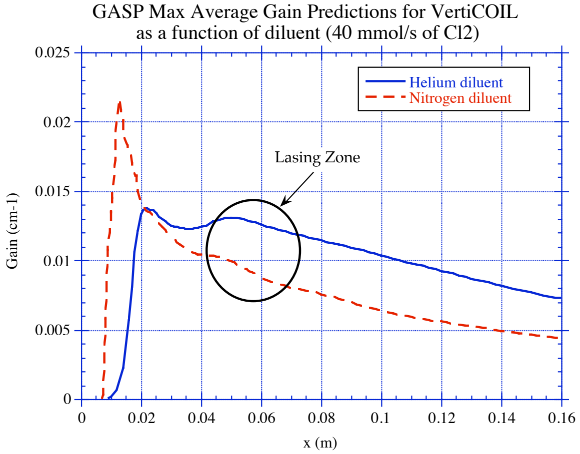

Fig. 3. GASP predictions of the maximum value of the average gain slice as a function of distance from the leading iodine injector for helium and nitrogen diluent.

It is quite interesting that the shape of the gain curve with pre-dissociated iodine is similar to that of the gain curve when nitrogen diluent is used, rather than helium, Fig. 3. Recent reported nozzle design improvements have been made for use with nitrogen diluent [Zagidullin, 1997; Azyazov, 1997; Furman, 1997; Endo, 1998; Nikolaev, 1998; Carroll, 1999]. Since the gain shape with nitrogen diluent is similar to that when injecting atomic iodine, it may be possible to use some of these recent design concepts to obtain significant performance enhancements when implementing a pre-dissociated iodine injection scheme. For example, Carroll *et al.* [Carroll, 1999] improved VertiCOIL performance with nitrogen diluent from 15.4% up to 23% chemical efficiency (nearly a 50% increase) by simply moving the injector position very close to the throat. Of course, this is only a similarity and it must be realized that the mechanisms occurring with nitrogen diluent are in fact fundamentally different, i.e., the nitrogen diluent case involves a slower velocity flow which allows the I_2 dissociation to occur quickly when injected in the subsonic portion of the flow. Thus, while the similarity in gain curves is interesting and may be useful, one must be aware that the final nozzle design may well be different between injecting atomic iodine into helium versus molecular iodine into nitrogen.

Several different innovative COIL nozzle concepts need to be investigated, Fig. 4. Among the possible nozzle concepts that are being considered are injection of iodine into the throat, sonic/supersonic injection into the supersonic flow, a combination of injection at the throat and sonic/supersonic injection into the supersonic flow, low speed injection through the boundary layer into the supersonic flow. Other candidates that show promise are the Cassady screen nozzle array [Cassady, 1978], staggered grid nozzle arrays, axisymmetric grid nozzle arrays, and supersonic/hypersonic injection via wedge injection blades in the supersonic flow. Aspects of the flow to be improved upon with the advanced nozzles will include mirror power loading, gain magnitude and distribution, chemical efficiency, and pressure recovery.

We believe that the key performance enhancement to the COIL nozzle technology is the combination of injection of pre-dissociated iodine and an appropriately redesigned nozzle that uses the atomic iodine efficiently in the laser region. Nozzle design issues have already been discussed at length above. The principle candidates for creating atomic iodine to inject into the primary flow are:

(1) RF discharge

RF discharge is a promising alternative that has been briefly investigated by the Japanese and Russians [Vagin, 1995], but to date the experimental chemical efficiencies have been well below those of conventional COIL. It is believed that the primary reason these experiments have underperformed expectations is a consequence of a poor nozzle design and injection scheme. Also, the RF discharge implemented by the Japanese may not have been of very good quality, so complete dissociation may not have been obtained.

(2) Chemical reactions

A possible chemical reaction that may be of interest is $F + DI \rightarrow DF + I$. The advantage of using such a reaction is that you are likely to obtain completely dissociated I atoms, so long as the flow is F atom rich. The disadvantage of such a combustion reaction is that the secondary flow of iodine atoms may be very hot, 600 K or higher; this will adversely influence the gain via an increase in Y_{th}, Eq. (3). The use of HI, rather than DI, was also considered, but was dismissed because the resulting HF molecules will absorb COIL photons since the HF overtone wavelengths overlap with the COIL wavelength of 1.315 μm. Other candidates to be considered would be those susceptible to breaking bonds in iodine containing molecules such as CH_3I, although their subsequent chemistry may make them ineffective.

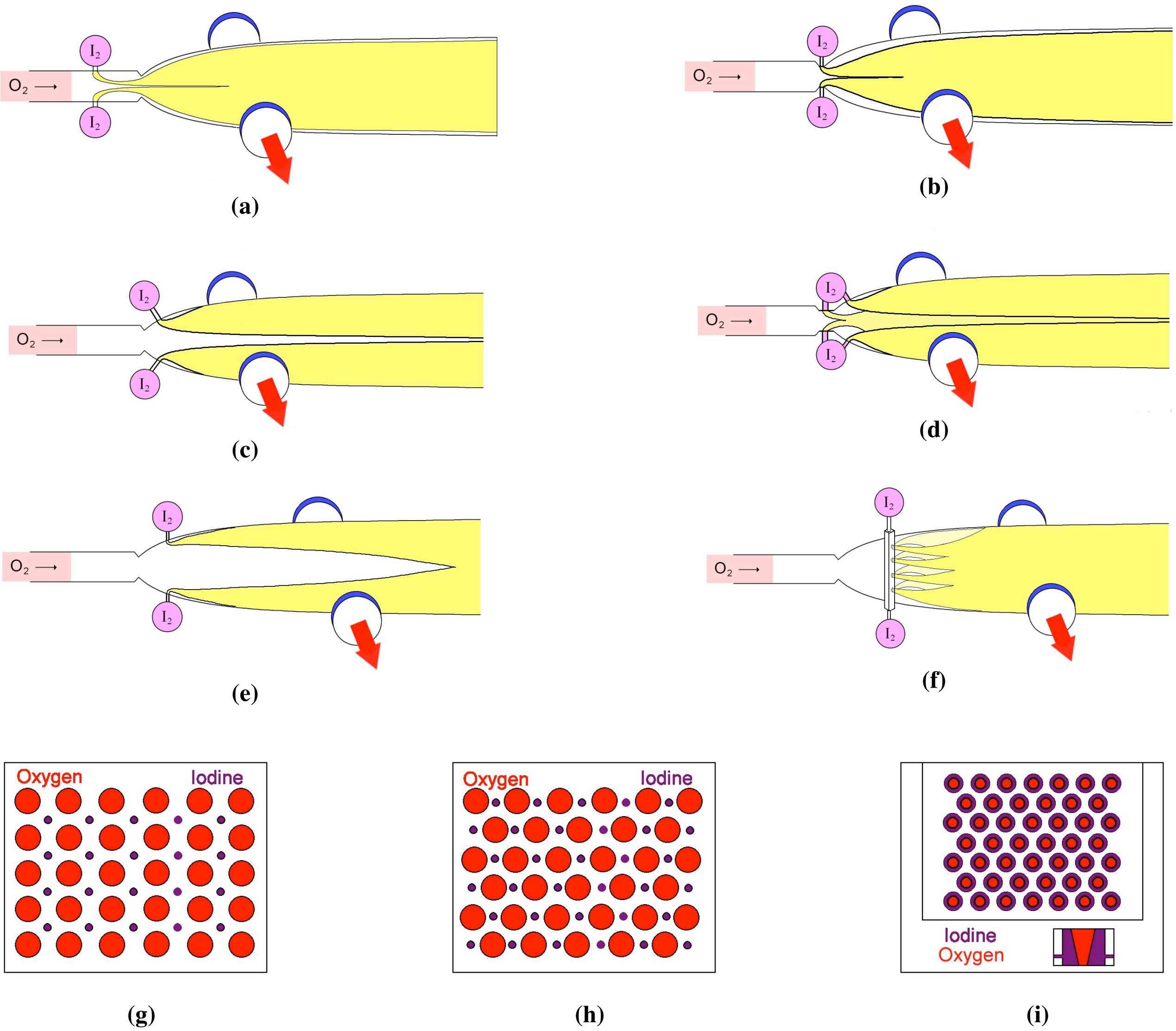

Figure 4. Illustrations of different nozzle concepts to be investigated. (a) Sonic injection into the subsonic stream, (b) sonic injection at the throat, (c) sonic or supersonic injection into the supersonic flow, (d) sonic injection at the throat plus sonic or supersonic injection into the supersonic flow, (e) low velocity injection into the boundary layer of the supersonic flow, (f) super/hypersonic wedges which inject into the supersonic flow, (g) Cassady-type grid nozzle, (h) staggered screen nozzle injection, and (i) an axisymmetric injection scheme.

(3) Thermal dissociation

High temperature thermal dissociation of molecular iodine is another option. Heating the iodine to 1000-1200 K will result in a large dissociation fraction of the initially molecular iodine. Since there are considerable logistic problems with maintaining such a high temperature for long flow distances through gas supply lines, this scheme would likely require a specialized secondary nozzle that would superheat the iodine and secondary diluent just prior to injection. This type of scheme was implemented by Bell Aerospace Textron in 1982 [Bell Aerospace Textron, 1982] in which two resistively heated 0.64 cm diameter platinum sidewall spray bars were used to inject a secondary iodine flow with a total temperature of 1200 K. It should be possible to utilize a high Mach number supersonic injector nozzle to drop the static temperature to more reasonable levels that would not seriously impact the gain via an increase in Y_{th}, Eq. (3).

(4) Photolytic pumping

Dissociation of molecular iodine via a photolytic pumping mechanism is a possibility. However, it can often be hard to obtain complete dissociation by photolysis. There are also serious scalability issues. For example, photolytic pumping would require flashlamps of some form, but a high power COIL would require large flashlamps to dissociate the larger flows of iodine. Another option is the possible use of a high intensity finger type arc lamp or quartz lamp, which would be able to both photolytically dissociate and add significant heat to help prevent recombination of the iodine.

These four iodine pre-dissociation techniques will be evaluated in the near term studies. The best potential candidate will be chosen and a preliminary design concept will be created.

To properly evaluate each nozzle design tested experimentally it is important to have high quality diagnostics. While a power measurement is useful in an overall integrated sense, it does not provide any of the flow details. Burn blocks or intensity profiles from scanning scattered radiation are also useful because they provide beam size and mode shape information which are important for evaluating the mirror loading aspects of different nozzles, but, again, this form of diagnostic tells you little about the flow details. The one diagnostic which stands out as being an essential tool to provide detailed information about each nozzle design is a precise small signal gain diagnostic. This diagnostic will give a detailed two-dimensional map of the gain and temperature profiles in the laser cavity region. This data can then be directly compared to the results from three-dimensional CFD computations. Other useful diagnostics are instruments for measuring water vapor, ground state oxygen (a yield measurement), Laser Induced Fluorescence (LIF), and a more sophisticated chlorine utilization diagnostic.

Computational Fluid Dynamics (CFD) is essential to understanding certain mixing and fluid dynamic details that probe diagnostics do not unveil due to their inherent averaging along the gain length. CFD research at UIUC has been conducted under a series of Air Force contracts awarded by Logicon/RDA and AFRL over the past six years. Under these contracts we have developed an extensive family of computational tools for COIL lasers. These computational tools are state-of-the art in the industry. The first of this series of tools is specifically targeted to describing the operational envelope for COIL systems, Blaze II, and has been extensively refined against data over many years. A new code for solid modeling of nozzle hardware, Unigraphics, has been in use on COIL projects for the past six months. Gridgen takes an arbitrary design from Unigraphics and establishes the detailed coordinates (the computational grid) for a CFD calculation. Our 3-D CFD calculations have progressed through several families of computational methods to the use of GASP Version 3.2.1 today, which is a reacting Navier-Stokes finite volume model. This CFD code is fully capable of parallel processor operation. This code has been carefully compared against data and MINT calculations over several years. We employ Tecplot for post processing of species, gain and fluid dynamic parameters. All of these tools are owned by or licensed to UIUC and have been employed extensively in the above contracts.

A summary of CFD research at UIUC is provided in Table 2. UIUC has completed or has in progress 12 COIL simulations. Five cases were run for RADICL [Madden, 1997], and seven cases have been run for the VertiCOIL system (two of which are in progress). A wide range of flow conditions were simulated providing reasonable agreement with experimental gain data for those cases in which gain data were available. In addition, UIUC has computationally modeled cases with both helium and nitrogen diluent for VertiCOIL; these computations aided the design of the nozzle/injector configuration which led to experimentally measured chemical efficiencies of 23% with nitrogen diluent. As mentioned earlier, it is felt that UIUC possesses state-of-art computational capabilities as good as any available in the industry.

Table 2. Summarized list of CFD cases completed or in progress using GASP at UIUC.

Laser	**RADICL**	**VertiCOIL**	**VertiCOIL**
Diluent	Helium	Helium	Nitrogen
# of Cases Run	5	3	4
Geometry	Nominal (0.35” throat)	Nominal (0.35” throat)	0.35-0.45” throat
Chlorine Flow (mmol/s)	499 - 503	40 - 70	40 - 70
Diluent Ratio	4:1 – 10:1	4:1	4:1
Titration Ratio	1.5 - 2.4%	1.7 - 2.1%	1.8 - 2.1%
Yield	0.38 – 0.66	0.61 – 0.66	0.51 – 0.62
Pressure (Torr)	72 - 126	35 - 69	40 - 108

Mirror loading for chemical lasers is an important issue, especially for very high-power military lasers. For example, a fairly uniform intensity profile is desired such that local hot spots, which tend to cause damage, do not develop on the laser mirrors. A beam shape attribute common to COIL systems is a 'sugar scooping' effect producing an intensity spike at the leading and trailing edges of the beam profile. One of the causes of this sugar scooping effect is that the leading edge of the laser mirrors is typically placed in a position of high average gain; this is a consequence of the classic COIL nozzle which produces significant positive gain ahead of the leading edge of the mirrors. From an experimental standpoint mirror loading can be judged by the shape of the beam, which can be determined simply from a burn block or more precisely by scanning a scatter plate or the use of a beam profiler. However, only a limited number of nozzle concepts need to be actually tested experimentally. To judge the mirror loading issue of other nozzle concepts we plan to consider each predicted gain curve and the I_2 dissociation fraction curve relative to the location of the mirrors.

Pressure recovery is extremely important where the weight of the diffuser system needs to be minimized. This issue must be addressed in the nozzle design process. Ultimately, the advanced nozzle concept must recover a substantial fraction of the flow total pressure. One possible scheme is the use of a high pressure, high Mach number secondary flow to add momentum to the total flow. This is essentially the idea behind a supersonic ejector system, but in this case you are inherently adding an ejector stage via the secondary nozzles themselves. Using a Cassady grid nozzle concept [Cassady, 1976], Nikolaev [Nikolaev, 1998] demonstrated that a 20 Torr total pressure primary flow combined with a 330 Torr total pressure secondary flow resulted in a recovered flow having a total pressure of 103 Torr.

4. Concluding Remarks

The ultimate results of this study will be innovative advanced mixing nozzles that will improve COIL chemical efficiencies above the 35% mark. The resulting family of advanced nozzles will be usable by DoD programs as well as evolving industrial COIL systems. By significantly improving COIL chemical efficiencies there will be considerable reductions in the gain generator subsystem weight and cost. Additional benefits that will come from this research will be a reduction in the loading on optical components and improvements in the pressure recovery of the nozzle, the latter aspect is particularly important to ABL. We feel that the resulting innovative concepts will have significant appeal to both the military and commercial customers.

The results of preliminary studies will lay the foundation for developing, fabricating and testing of highly advanced COIL mixing nozzles at a later date. These nozzle concepts will logically include injection of atomic rather than molecular iodine and will likely be a supersonic jet injected into the supersonic portion of the main nozzle. The well calibrated and economical COIL facility at UIUC will allow a number of advanced nozzle concepts to be implemented and examined in detail; this should be of great benefit to DoD and to the research and development of more sophisticated nozzles for use in a commercial COIL device.

References

Azyazov, V., Zagidullin, M., Nikolaev, V., and Safonov, V. (1997). *Quantum Electronics* **27**, 6, 477 (*Kvantovaya Elektronika* **24**, 6, 491).

Bell Aerospace Textron (1982). "Proposal for Oxygen-Iodine Supersonic Technology Program, Part III, Section II," Report No. D9299-953003, p. 4.1-21.

Carroll, D. (1995). *AIAA Journal*, **33**, 8, pp.1454-1462.

Carroll, D. (1996). "Optimizing High Pressure Chemical Oxygen-Iodine Laser," Proc. of the Int. Conf. on Lasers'95, eds. V. Corcoran and T. Goldman, STS Press, McLean VA, 225.

Carroll, D. and Rothenflue, J. (1997). *J. of Laser Applications*, **9**, 3, 119.

Carroll, D., King, D., Fockler, L., Stromberg, D., Solomon, W., Sentman, L., and Fisher, C. (1998). "COIL for Industrial Applications," AIAA Paper 98-2992.

Carroll, D., King, D., Fockler, L., Stromberg, D., Solomon, W., Sentman, L., and Fisher, C. (1999). "Performance of a High Power Chemical Oxygen-Iodine Laser using Nitrogen Diluent," accepted for pub. in *IEEE J. of Quant. Elec.*

Cassady, P.E., Newton, J.F., and Rose, P.N. (1978). *AIAA Journal*, 16, 4, pp. 305-312.

Endo, M., Nagatomo, S., Takeda, S., Zagidullin, M., Nikolaev, V., Fujii, H., Wani, F., Sugimoto, D., Sunako, K., Nanri, K., and Fujioka, T. (1998). *IEEE J. of Quant. Electronics*, **34**, 3, 393.

Furman, D., Barmashenko, B., and Rosenwaks, S. (1997). *Appl. Phys. Lett.* **70**, 18, 2341.

Helms, C., Shaw, J., Hager, G., and Truesdell, K. (1994). AIAA Paper 94-2437.

Helms, C. (1996). Private communcation.

Helms, C., Rittenhouse, T., Phipps, S., Truesdell, K., and Hager, G. (1997). "Extraction efficiency of a 5-cm gain length supersonic chemical oxygen-iodine laser," Proc. of the Int. Conf. on Lasers '96, Corcoran, V. and Goldman, T., eds., STS Press, McLean, VA, 188.

Hon, J., Hager, G., Helms, C., and Truesdell, K. (1996). *AIAA Journal*, **34**, 8, 1595.

Kar, A., Carroll, D., Latham, W., and Rothenflue, J. (1998). "Cutting Performance of a Chemical Oxygen-Iodine Laaser on Aerospace and Industrial Materials," accepted for publication in *J. of Laser Applications*.

Keating, P, Helms, C., Anderson, B., Rittenhouse, T., Truesdell, K., and Hager, G. (1997). "Two-dimensional Gain and Cavity Temp. Maps of a Small-Scale Supersonic COIL," Proc. Int. Conf. on Lasers'96, eds. V. Corcoran and T. Goldman, STS Press, McLean VA, 194.

Kendrick, K., Helms, C., Hager, G., Copland, R., and Crowell, P. (1998). "Recent Water and Oxygen Measurements on a 10 kW Chemical Oxygen-Iodine Laser," presented at the Int. Conf. on Lasers'98, Tucson, AZ, Dec. 7-11, 1998.

Madden, T.J. (1997). Ph.D. Thesis, University of Illinois at Urbana-Champaign.

Madden, T., Hager, G., Lampson, A., and Crowell, P. (1998). "Computational Fluid Dynamic Investigation of Supersonic Mixing Mechanisms for the Chemical Oxygen-Iodine Laser (COIL)," presented at the Int. Conf. on Lasers'98, Tucson, AZ, Dec. 7-11, 1998.

McDermott, W., Pchelkin, N., Benard, D., and Bousek, R. (1978). *Appl. Phys. Lett.* **32**, 8, 469.

Nikolaev, V. (1998). "Comparative analysis of the different methods of preparing active medium in supersonic COIL," summary paper, P.N. Lebedev Physical Institute, Samara Branch, Chemical & Electrical Discharge Lasers Laboratory, Samara, Russia.

Plummer, D., Heidner, R., and Perram, G. (1988). "The Proceedings from the 1987 Air Force Weapons Laboratory Conference on Chemical Oxygen-Iodine Laser (COIL) Kinetics (held on 11 August 1987)," RDA/Logicon, R&D Associates, Albuquerque, NM.

Rittenhouse, T, Phipps, S., and Helms, C. (1998). "Performance of a High-Efficiency 5 cm Gain Length Supersonic Chemical Oxygen-Iodine Laser," *IEEE J. of Quantum Electronics*, **35**, 6, 857 (1999).

Scott, J., Shaw, J., Truesdell, K., Hager, G., and Helms, C. (1994). AIAA Paper 94-2436.

Sentman, L., Subbiah, M., and Zelazny, S. (1977). "Blaze II: A Chemical Laser Simulation Computer Program," Bell Aerospace Textron, Buffalo, NY, T.R. H-CR-77-8.

Tate, R., Hunt, Helms, C., Truesdell, and Hager, G. (1995). *IEEE J. of Quant. Elec.*, **31**, 9, 1632.

Truesdell, K., Lamberson, S., and Hager, G. (1992). AIAA Paper 92-3003.

Truesdell, K., Helms, C., Frerking, S., Hager, G., Plummer, D., and Copland, R. (1996). "COIL performance modeling and recent advances in diagnostic measurements," *XI Int. Symp. on Gas Flow and Chemical Lasers and High Power Lasers Conf.*, SPIE, Vol. 3092, 676.

Vagin, N., Pazyuk, V., and Yuryshev, N. (1995). *Kvantovaya Elektronika* (in Russian), **22**, 776.

Yang, T., Copeland, D., Bauer, A., Quan, V., McDermott, W., Cover, R., and Smith, D. (1997). AIAA Paper 97-2384.

Zagidullin, M., Nikolaev, V., Svistun, M., Khvatov, N., and Ufimtsev, N. (1997). *Quantum Electronics* **27**, 3, 195 (*Kvantovaya Elektronika* **24**, 3, 201).