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Performance of a Multi-Stream Injection COIL with Starlet Ejectors

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A variant of an ejector mixing nozzle for a chemical oxygen-iodine laser (COIL) was experimentally tested with notched "starlet" ejectors. Cold flow planar laser induced fluorescence (PLIF) measurements indicate that the starlets provide faster mixing. Hot flow testing demonstrated that the starlet design improved laser performance by 20-30% above the basic cylindrical ejector design. Further, a conical ejector design with starlet notches was also tested that resulted in approximately a 15% improvement above the cylindrical design and has the potential for higher pressure recovery. Pressures in the singlet oxygen generator (SOG) were relatively constant with ejector flow rate suggesting that existing high efficiency SOGs can be used with this ejector nozzle configuration without sacrificing generator performance for pressure recovery potential.

I. Introduction

The chemical oxygen-iodine laser (COIL) was first demonstrated in 1978 [McDermott, 1978]. Since that initial demonstration, COIL technology has undergone numerous improvements [Truesdell, 1992; Zagidullin, 1998; Kodymova, 2007, Endo, 2007]; chemical efficiencies as high as 36-40% using nitrogen diluent have been demonstrated [Rybalkin, 2005]. Much of the COIL technology development to date has focused on the singlet-oxygen generator (SOG). The liquid SOG technology has developed to a fairly mature state. However, much of the work has been performed at relatively low pressures (20-60 Torr) with poor pressure recovery potential. The ability to increase the total pressure and Mach number of the flow, while at the same time maintaining good iodine mixing, cavity kinetics, and generator pressure can have a dramatic impact on the overall system by simplifying the pressure recovery system (by reducing the amount of fluids and weight of ejector hardware) [Boreysho, 2009].

One of the major thrusts in COIL technology in the past decade has been to increase the total pressure of the system for better pressure recovery and to find novel schemes to enhance the iodine mixing in such high pressure systems. Studies by Nikolaev [Nikolaev, 2000; Nikolaev, 2002] and Yang [Yang, 2000] with ejector-mixing nozzles along with detailed modeling [Waichman, 2009; Madden, 2010] have provided important insights into the nozzle mixing issue and COIL pressure recovery performance. The ejector mixing nozzle concept put forward by the Russian Lebedev Physical Institute research group at Samara [Nikolaev, 2000] appears particularly promising and the design evolved through later work over several years [Zagidullin, 2001; Khvatov, 2002; Hager, 2003; Zagidullin,

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2005]. The research discussed herein directly addresses gain generator mixing efficiency for systems having higher pressure recovery potential over the baseline while maintaining singlet oxygen generation and transport efficiency.

The idea of the "Starlet" nozzle concept stems originally from experimental work of Pannu and Johannesen [Pannu, 1976]. Pannu and Johannesen reported results on a series of experiments concerning sonic flow from tubes with V-shaped slots cut into the end of the tube. Our interest in these experiments concerns the flow field generated by the slots that creates two counter-rotating vortices at each notch and that these vortices generate a large outward flow velocity thereby stretching the surface of the mixing interface. This work was then applied to mixing in chemical lasers by Solomon *et al*. [Solomon, 1982] who pioneered the "Star" nozzle concept in which tubes with four notches created a "star" pattern when visualized by laser induced fluorescence techniques. The "Starlet" nozzle concept [Carroll and Solomon, 2009] is a variant design of the source flow ejector mixing nozzle studied by Nikolaev *et al*. in which notches are added to create a high degree of strain or fluid stretch to accelerate the molecular mixing. Practical considerations dictate the nozzle hardware be simple, flexible, and easy to manufacture, and these factors also played a major role in the evolution of the Starlet nozzle design.

The VertiCOIL system [Rittenhouse, 1999; Carroll, 2000] with roto-SOG serves as our "baseline" point of departure for the more advanced work conducted herein. VertiCOIL was originally developed and tested at the Air Force Research Laboratory (AFRL) [Rittenhouse, 1999; Keating, 1997], and was transferred to the University of Illinois at Urbana-Champaign (UIUC) on a technology transfer program to conduct additional work with helium and nitrogen diluent using modified nozzle hardware [Carroll, 2000]. The VertiCOIL system is well characterized in terms of laser performance with both helium and nitrogen diluent. The facility provides performance data that can be directly connected to the earlier technology database in a believable and cost effective manner, i.e., the precise efficiencies of the tested nozzle technologies in terms of typical laser variables (flow rates, temperatures, small signal gain, etc).

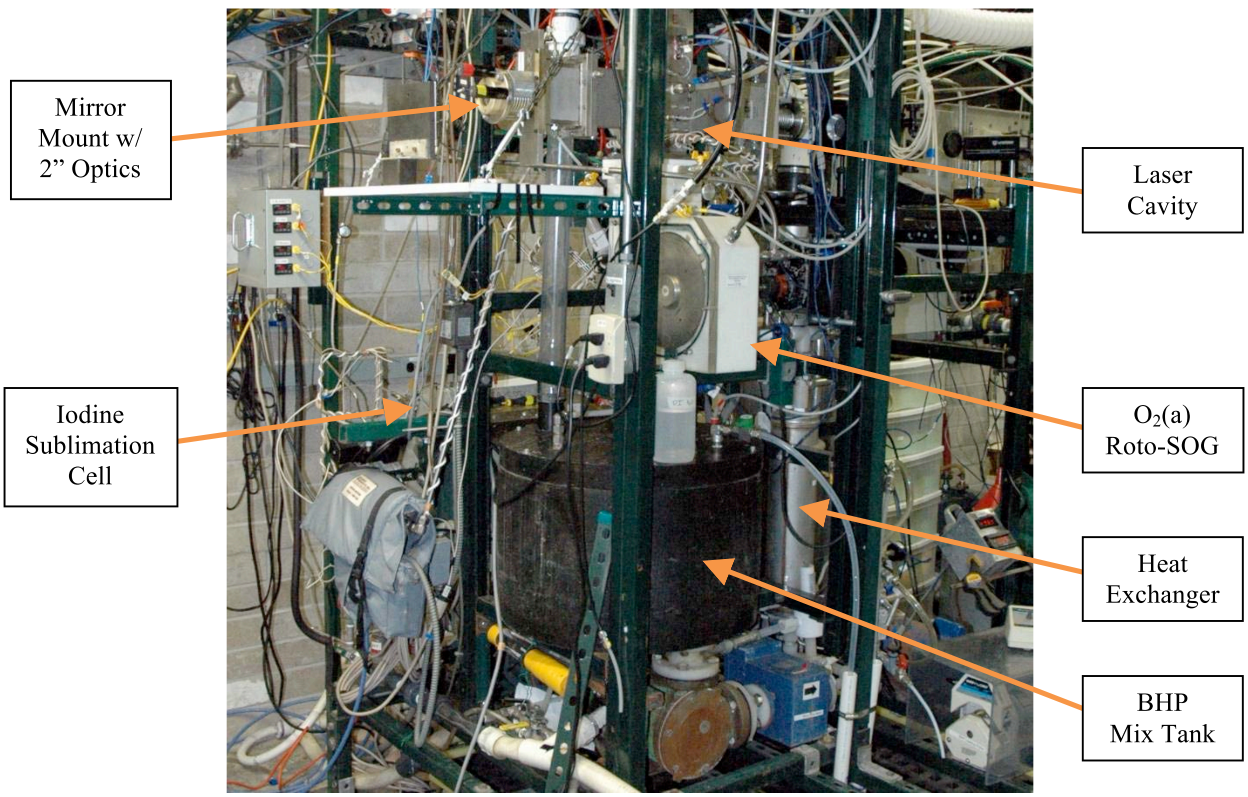

Figure 1. COIL test setup with VertiCOIL roto-SOG, cavity, and nozzle.

II. Experimental Setup for Gain and Lasing Testing

The majority of the experimental setup is essentially that of the VertiCOIL hardware detailed by Rittenhouse *et al.* [Rittenhouse, 1999] and Carroll *et al* [Carroll, 2000]. While much of the structure and hardware necessary to operate an ejector nozzle COIL was already in place, some updated flow diagnostics, gas feed lines, and pressure transducers, as well as a new laser cavity for the new nozzle/ejector(s) and various other experimental hardware needed to be either reconfigured or designed and manufactured for this work. As such, the CUA-UIUC team updated, upgraded, and reconfigured the existing COIL (VertiCOIL) hardware for the lasing experiments detailed in Sect. III.

A photograph of the VertiCOIL test bed is shown in Fig. 1 and in diagram form in Fig. 2. The key components of the device include the basic hydrogen peroxide (BHP) mix tank, the liquid nitrogen (LN_2)-Syltherm-BHP heat exchanger, the rotating disk SOG (or "roto-SOG"), the transition duct, the laser cavity, the laser nozzle, the mirror ducts / mounts, and the vacuum system. Support systems such as gas flow delivery, chemical analysis, safety, and data acquisition (DAQ) were also updated to accommodate new demands.

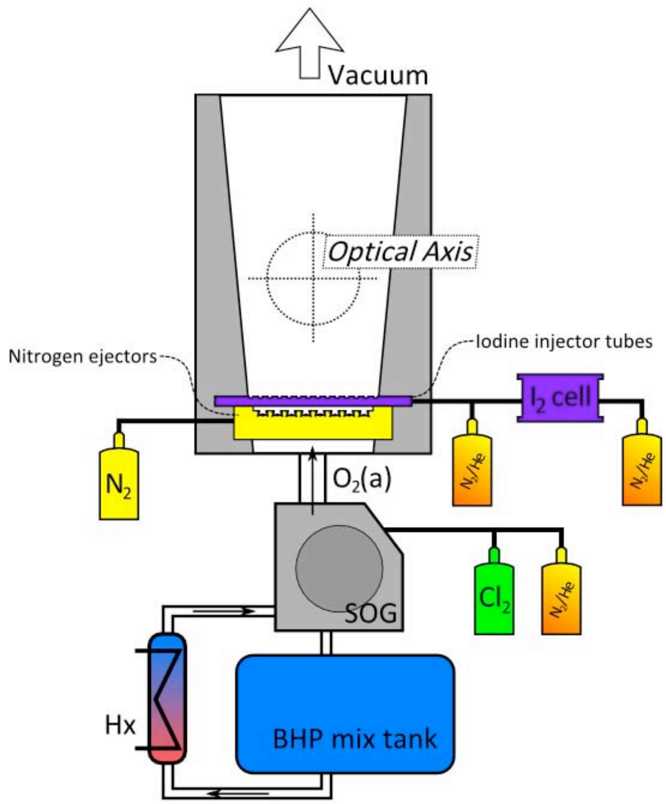

Figure 2. Schematic of COIL device elements (shown with new ejector nozzle).

All subsystems were tested for proper functionality prior to the commencement of cold flow and hot flow testing. As the final part of the system functionality testing, we established that the device was performing the same as previous hot fire performance levels with the original VertiCOIL nozzle [Rittenhouse, 1999; Carroll, 2000].

Cold-flow PLIF and schlieren testing [Ragheb, 2010a; Ragheb, 2010b] on a smaller hardware setup was performed for several different ejector sets: (i) small cylindrical ejectors having a diameter of 0.058", (ii) small cylindrical ejectors with the notched starlets, (iii) large cylindrical ejectors having a diameter of 0.087", (iv) large cylindrical ejectors with the notched starlets, (v) conical ejectors with a geometric area corresponding to a Mach 2 exit flow, and (vi) Mach 2 conical ejectors with notched starlets at the exit (note: PLIF results from the first two and latter two configurations are shown in Sect. 3.1). The results of the PLIF testing [Ragheb, 2010a; Vorobieff, 2010] indicated that the fastest mixing was obtained with the starletted small cylindrical ejectors with the next fastest being the small cylindrical ejectors. Starletted large ejectors showed significantly faster mixing than the large cylindrical ejectors. While the starletted conical ejectors show significantly faster mixing than the conical ejectors, the starletted conical ejectors were still slower mixing than the large starletted cylindrical ejectors. Because of the expense of hot-fire testing and the cost of manufacturing, we downselected to three ejector sets for hot-fire testing: (i) small cylindrical ejectors, (ii) small cylindrical ejectors with starlets, and (iii) conical ejectors with starlet notches at the exit.

2.2 Ejector Mixing Nozzle Hardware

The original VertiCOIL laser cavity housing required that the entire housing be uninstalled to clean the hardware between hot fire operations. To simplify operation, a new cavity was designed that was larger, with opposing walls containing 5.0” x 10.5” openings for the simple, rapid installation of multiple nozzle concepts, Fig. 3. To validate the new cavity and demonstrate that the added internal volume did not cause any undue recirculation zones, surface reactions, or changes to the resonator length sufficient to impact performance, the VertiCOIL nozzle was installed in the new housing and performance was replicated.

Figure 4 shows an illustration of the ejector nozzle hardware that was tested for gain and laser performance. The hardware was modular such that different ejector inserts could be tested with relative ease. The different ejector nozzle hardware configurations that were downselected for hot fire testing were fabricated, Figs. 5-7. A fourth configuration that also received limited testing was one in which the I_2 injector tubes were rotated 45° to point in towards the $O_2(^1\Delta)$ flow at an angle (normally the I_2 injectors were directed in the flow direction); this test was only performed with the small starlet ejectors. The assembled new laser cavity housing with the VertiCOIL nozzle inside, mounted on top of the roto-generator, is shown in Fig. 8.

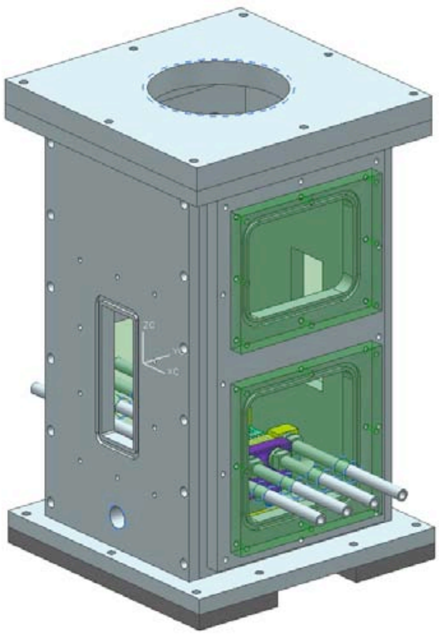

Figure 3: Hot-fire hardware installed in laser cavity housing.

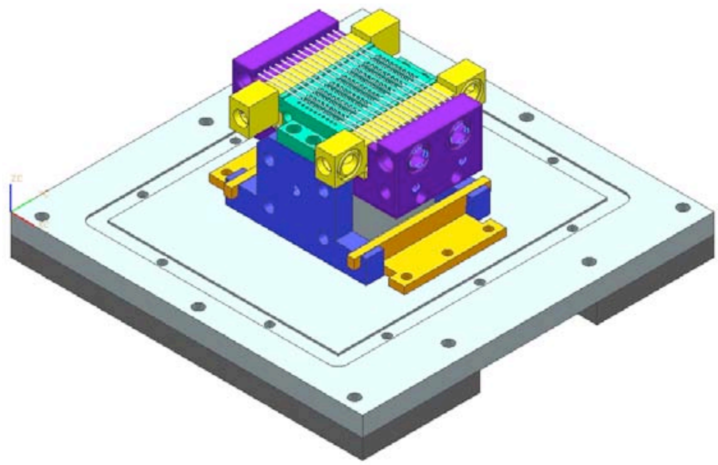

Figure 4: Hot-fire hardware attached to bottom wall.

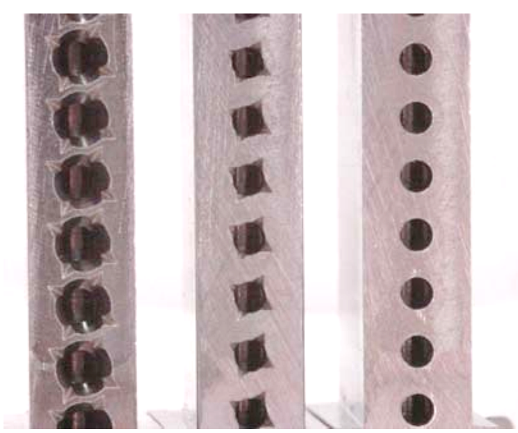

Figure 5: All three ejector nozzle concepts (conical starlets left, small cylindrical starlets center, and small cylinders right)

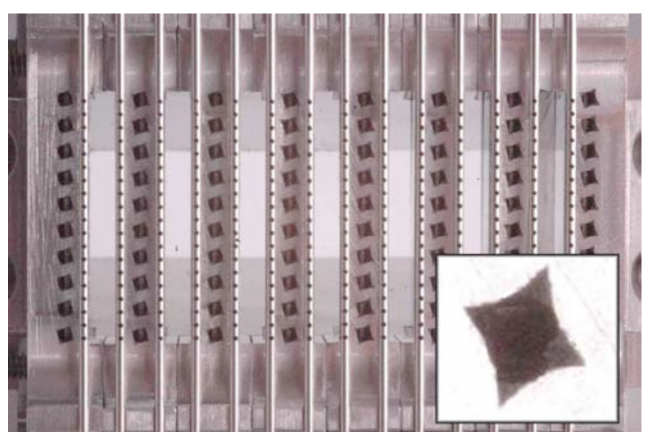

Figure 6: CUA-UIUC advanced “Starlet” (see inset) ejector nozzle hot-fire hardware.

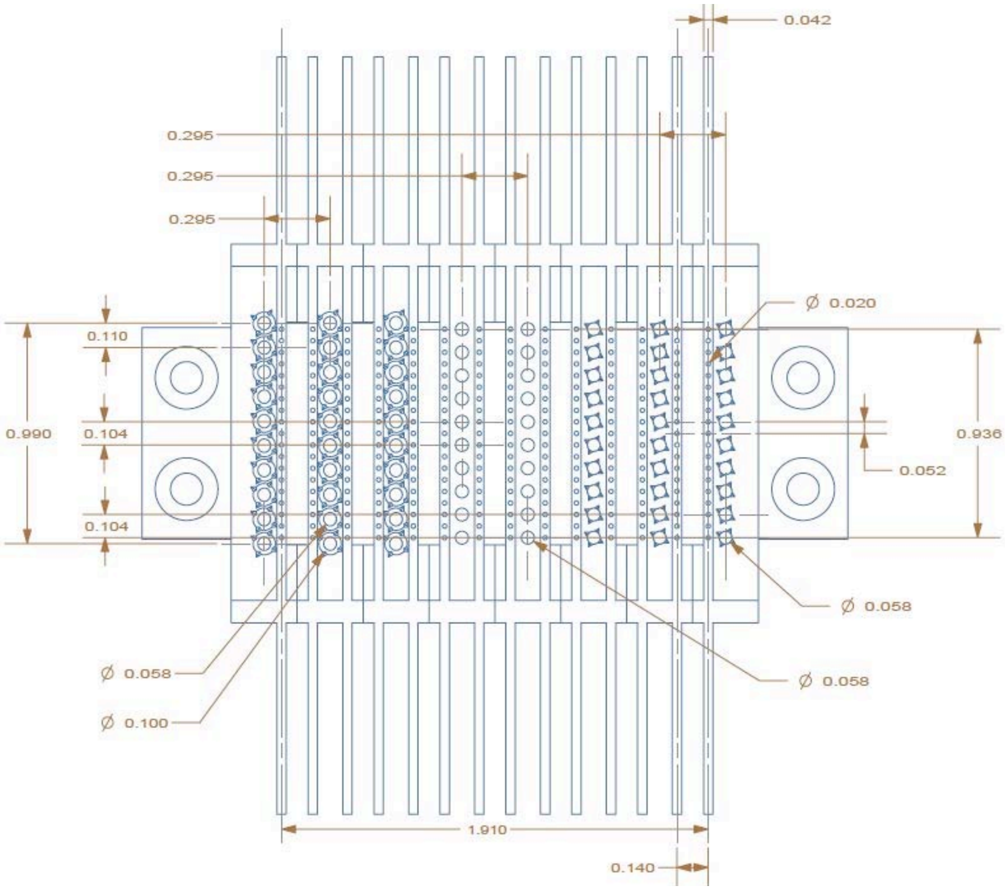

Figure 7: All three ejector nozzle concept inserts shown installed into a single ejector assembly (note conical starlets left, cylinders center, and starlets right). All dimensions in inches.

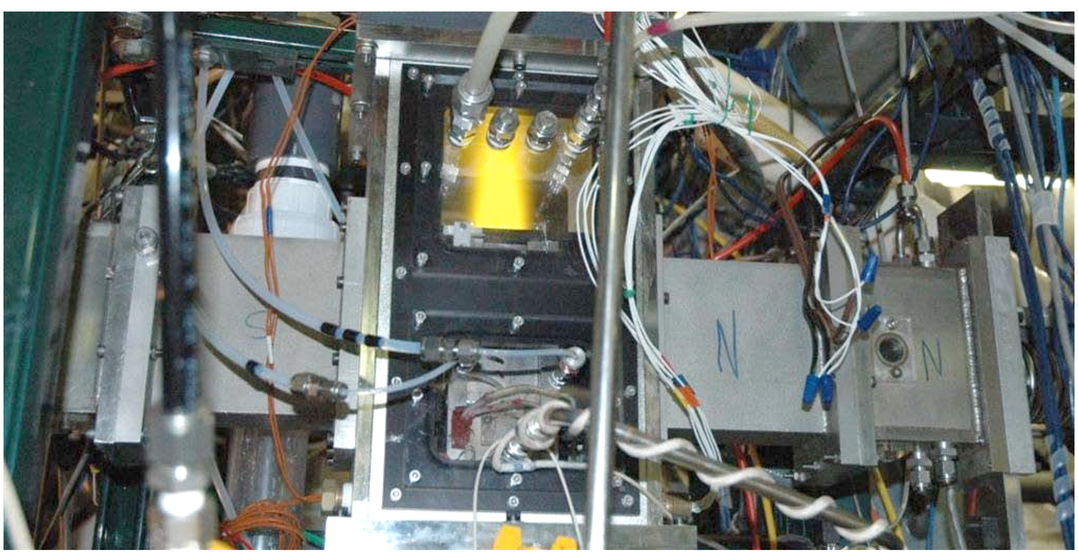

Figure 8: VertiCOIL nozzle installed and tested in new cavity housing [note visible yellow I_2(B) emission downstream of nozzle exit].

Although the mirror-duct-to-cavity fixture is static, a translation of the final optic mount in the flow direction permits slightly greater than 2.5" of adjustment in the optical axis downstream of the iodine injection plane, Fig. 9. Ramps with a constant expansion angle of 2.4° were added downstream of the nozzle ejector plane to confine the flow while allowing for heat release, Fig. 9. The pressure in the lasing cavity was approximately constant with the expansion ramps installed.

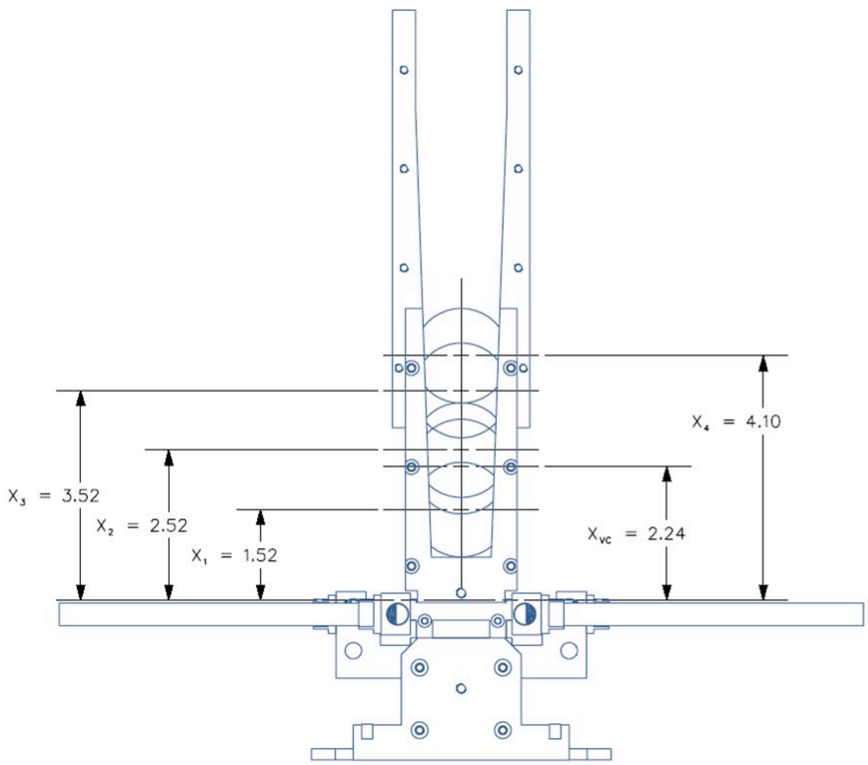

Figure 9. Ejector nozzle optical axis positions illustrated with 2" diameter optic centered on the optical axis positions. Note that the X_{VC} denotes the distance that the VertiCOIL nozzle optical axis is located relative to the VertiCOIL rows of iodine injection (dimensions in inches). Also shown are the 2.4° expansion ramps in the laser cavity region.

III. Experimental Results

3.1 PLIF Experiments with Conical and Conical Starlet Ejectors

The PLIF series of Ragheb *et al*. [Ragheb, 2010a] was completed by testing: (a) conical ejectors with a geometric area corresponding to a Mach 2 exit flow, and (b) Mach 2 conical ejectors with notched starlets at the exit, Fig. 10. The experimental setup for these smaller scale (only 4 columns of ejectors) cold-flow tests is detailed in Ragheb *et al*. [Ragheb, 2010a]. For brevity, only the location nearest the ejector plane (1.27 cm downstream) is shown below in Fig. 10 in a comparison between small cylinders, small starlets, conical ejectors, and conical starletted ejectors. It appears that the starlet case has a wider iodine field than the cylinders, for all three ejector flow rates, indicating that the starlets are mixing faster. Also, the starlets show a zigzag iodine pattern indicating that the iodine is spreading out along a diagonal path corresponding to the 30° rotation of the starlet notches as expected. While the conical and conical starlet ejectors have the greatest pressure recovery because of their supersonic nature (for brevity here, pressure recovery is to be the subject of another paper), it is also evident that they demonstrate slower mixing. However, comparing the PLIF imagery of conical starlets to the conical ejectors, it is clear that for the higher flow rate cases that there is faster mixing taking place with the conical starlets.

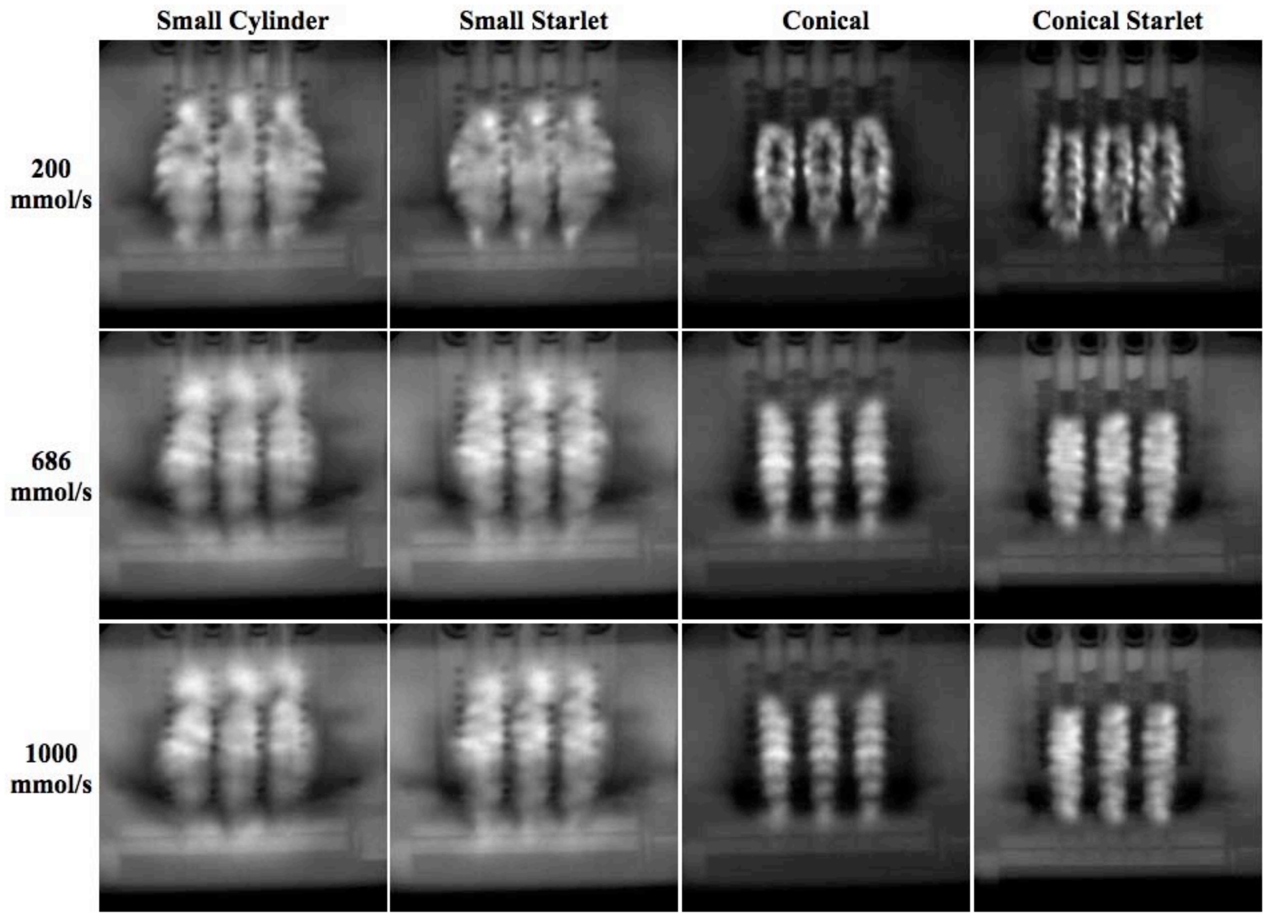

Figure 10: PLIF imaging experiments with small scale cold-flow hardware detailed in Ragheb et al. [Ragheb, 2010a] comparing four ejector geometries, including the conical starlets (far right column), at three ejector flow rates (imaging plane is located 1.27 cm downstream from the ejector plane).

3.2 VertiCOIL Verification Testing

As a startup to the hot flow testing for this program, a short series of tests with the VertiCOIL nozzle were conducted to confirm performance of the roto-SOG and laser and to verify the auxiliary and support systems during hot-fire operation. A peak output power of 1736 W was obtained with He diluent having a chemical efficiency of 21.6%. A peak chemical efficiency of 23.3% was obtained with an output power of 846 W and He diluent. Using N_2 diluent in the roto-generator, we obtained a peak power of 938 W with a chemical efficiency of 15.2%, and a peak chemical efficiency of 21.0% with a power output of 490 W. The peak gains recorded were 1.4 %/cm with He diluent and 0.9 %/cm with N_2 diluent, Fig. 11. Temperatures extracted from the gain lineshapes were ≈ 250 K, higher than those measured by Keating et al. [Keating, 1997] by ≈ 30-40 K; the reason for this discrepancy is unknown at present.

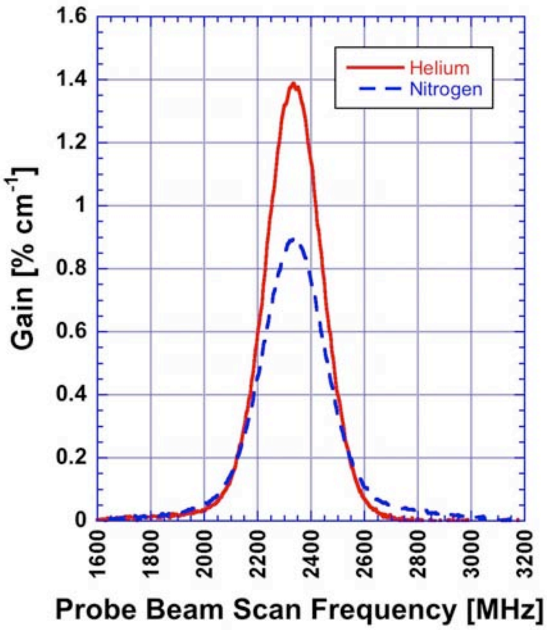

Figure 11: Peak gain profiles for helium and nitrogen diluted cases for the VertiCOIL nozzle and laser cavity.

Black 0.5" acrylic sheet was cut into 4" x 4" pieces to serve as burn blocks to record the beam shape. The blocks were positioned near the outcoupling optic inside an actively-vented transparent acrylic hood and exposed to the laser beam for short periods of time. Several burn blocks were taken with the VertiCOIL nozzle. A sample burn block taken over a laser-on period of 3 sec is shown in Fig. 12. This block shows a near-field beam size of 2.2 cm x 3.1 cm for a 1050 W laser beam. Remote video capability was added using a TRENDnet TV-IP410 Pan/Tilt Internet CCD Camera, Fig. 13.

Figure 12: 1050 W burn block (the flow direction is from the bottom to the top of the page) for a 3 s burn, 70 mmol/s of Cl_2, 280 mmol/s of He VertiCOIL test.

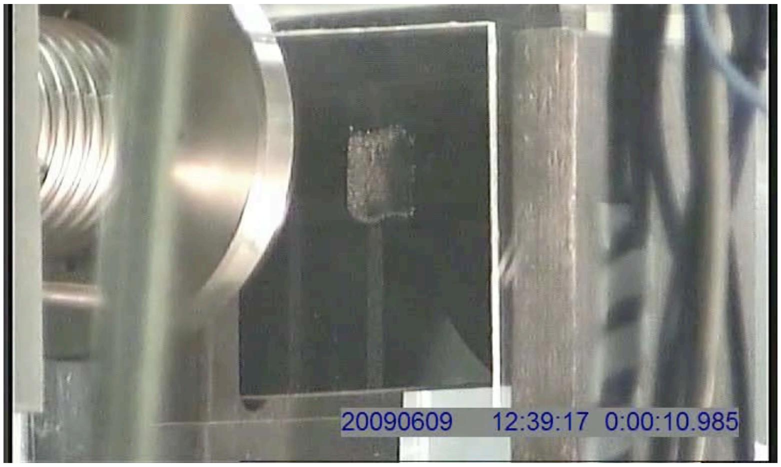

Figure 13: Remote video image from TRENDnet TV-IP410 Pan/Tilt Internet CCD Camera Server that enabled real time observation and recording of burn blocks.

An interesting test and discovery was that it was possible to observe the outcoupled laser beam shape on the face of the power meter, Fig. 14. The remote CCD camera was found to be sensitive enough in the infrared to observe the beam shape as a distinct lavender emission on the face of the power meter's thermopile. This was an invaluable discovery for operations as it provided an instant indicator of any potential mirror misalignments or other issues without having to stop the test and take burn blocks. It was also found that the beam shape viewed on the CCD was a close match to burn block impressions. Digital recordings of beam shapes for many laser tests were taken.

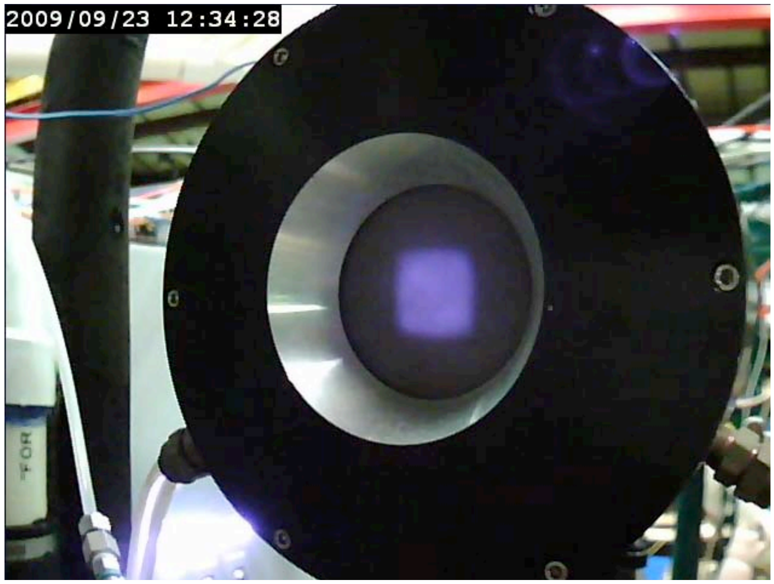

Figure 14: Infrared laser beam on water-cooled 5 kW thermopile power meter. The beam is being viewed remotely by a TRENDnet TV-IP410 Pan/Tilt Internet CCD Camera Server that has a small sensitivity to infrared radiation and enabled real-time observation of beam shape and size.

The VertiCOIL verification data are consistent with prior data taken by Carroll *et al*. [Carroll, 2000] with the VertiCOIL system using a 6.6 Molar HO_2- BHP mixture, thereby verifying the performance of VertiCOIL. This gave us the confidence to move forward with testing of the new hardware. The first such test was to put the VertiCOIL nozzle into the new laser cavity housing, Fig. 9; results were essentially identical between the new and old laser cavity housings, thereby verifying that the new cavity housing was performing as anticipated. Note that the new housing is more flexible and allows easier interchange/modification of internal hardware than the original.

It is important to note that operationally we were limited to using 50% H_2O_2 in our BHP mixtures due to limited bulk availability of higher concentration H_2O_2, which in turn limited our BHP mixtures to 6.6 Molar. This results in lower Cl_2 utilizations and $O_2(^1\Delta)$ yields from our roto-SOG as compared to AFRL VertiCOIL data taken by Rittenhouse *et al*. [Rittenhouse, 1999] in which 70% H_2O_2 was used in mixtures to generate 7.5 Molar BHP. Comparing the experimental data above and from [Carroll, 2000] with that of [Rittenhouse, 1999] indicates that the resulting performance penalty in terms of chemical efficiency is historically approximately 4%, e.g., Rittenhouse *et al*. report 27% chemical efficiency with He diluent, whereas we obtained 23%. Similarly, the peak gain measured by Keating *et al*. [Keating, 1997] with 70% $H_2O_2$was 1.67 % cm^{-1} vs. our measurement of 1.4 % cm^{-1} with 50% H_2O_2. *As such, we strongly believe that all data presented in this paper with our roto-SOG and BHP mixture can be readily improved upon by as much as 4-5 percentage points in terms of chemical efficiency by simply employing 70% H_2O_2 instead of 50% H_2O_2.*

An important point to note and carry forward is that the prior Russian experiments with the cylindrical ejector mixing nozzles used more advanced, more efficient jet-type and droplet-type SOGs with 7.5 Molar BHP [Zagidullin, 2005]. In the Russian work with cylindrical ejector-mixing nozzles they were able to obtain chemical efficiencies of approximately 20%, and as such we *a priori* anticipated that we would achieve approximately 15-16% chemical efficiency with our cylindrical ejector tests because of our use of a less-efficient SOG and reduced molarity BHP.

3.3 Ejector Nozzle Performance

Due to the many possible configurations of ejector nozzle hardware, flow rates, and optical axis locations, the large possible test matrix was reduced to best establish trends in a time and cost effective manner. Trends were established for optic axis location (Sect. 3.3.1), ejector flow rate (Sect. 3.3.2), I_2 flow rate (Sect. 3.3.3), primary diluent flow rate (Sect. 3.3.4), gain (Sect. 3.3.5), power and chemical efficiency as a function of Cl_2 flow rate (Sect. 3.3.6).

3.3.1 Optical Axis Location Effect on Laser Performance

Early testing with the main three ejector configurations focused on determining the best location to place the optical axis. Three optical axis locations were tested: X_1 = 3.86 cm, X_2 = 6.40 cm, and X_3 = 8.94 cm, Fig. 9. The laser power results are shown in Figs. 15 and 16 and indicate that for all configurations that the best position to locate the optical axis is approximately at X_2 = 6.40 cm. This result is interesting and perhaps not surprising for many reasons:

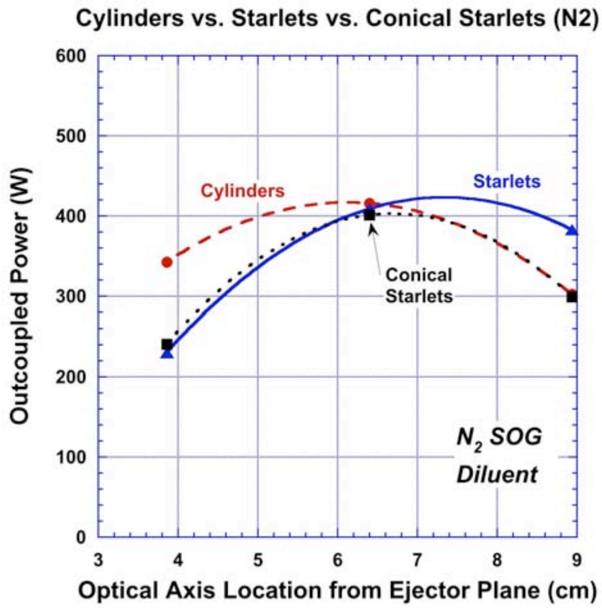

Figure 15: Outcoupled laser power versus the position of the optical axis from the ejector plane when using cylindrical, starlet, and conical starlet ejectors. The Cl_2 flow rate was ≈ 30 mmol/s buffered with ≈ 30 mmol/s of N_2 diluent in the roto-SOG.

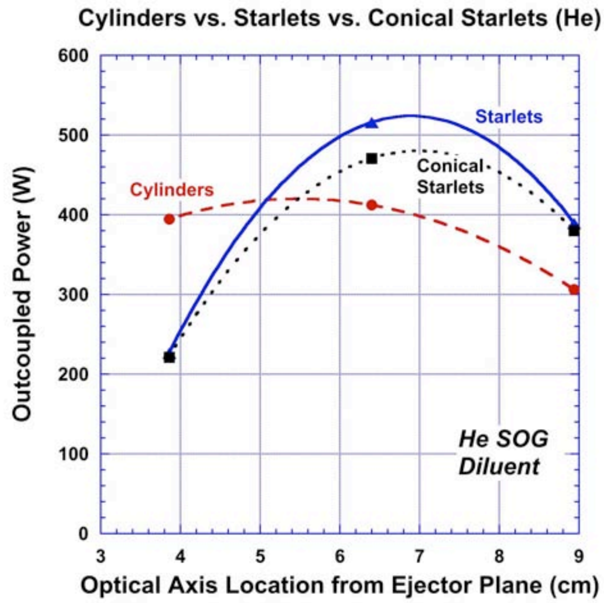

Figure 16: Outcoupled laser power versus the position of the optical axis from the ejector plane when using cylindrical, starlet, and conical starlet ejectors. The Cl_2 flow rate was ≈ 30 mmol/s buffered with ≈ 30 mmol/s of He diluent in the roto-SOG.

1) The X_1 position has a mirror leading edge that is approximately 1.4 cm downstream from the ejector exit plane. From the PLIF data [Ragheb, 2009a; Vorobieff, 2010], the flow is not well mixed until somewhere between 2.54 – 5.08 cm from the ejector exit plane, so it is not surprising that power would be lower in the X_1 position.
2) The X_3 position is the furthest downstream location that would correspondingly have the greatest kinetic losses, so it is not surprising that the power measured at X_2 was greater than that measured at X_3.
3) One interesting feature that was not anticipated was that because the PLIF imagery (Fig. 10) indicates slower mixing with the conical starlets than with the starlets and cylindrical ejectors (likely due to higher velocity flow), we *a priori* expected that the conical starlets would peak further downstream than the starlets and cylindrical ejectors. However, this was not the case as Figs. 15 and 16 clearly show; the conical starlets also had a performance peak at position X_2, which probably represents a trade-off between mixing and kinetic losses.
4) Another somewhat surprising result was that the performance of the cylinders was better than the starlets at the X_1 position; we presently do not understand this result (as it seems to suggest faster mixing with the cylinders whereas the PLIF data show the opposite), however it is somewhat irrelevant since the performance for all configurations was best with the mirror optical axis located at X_2. Modeling will be performed in the future to better understand this phenomenon.
5) The data for the cylindrical ejectors show little difference between the use of He or N_2 as the SOG diluent, however, the starlet and conical starlet data show the *a priori* expected increase in performance when using He as the SOG diluent (as is the case for the baseline VertiCOIL performance discussed previously).
6) The work of Nikolaev *et al.* [Nikolaev, 2000] indicated laser performance was better with the optical axis located at 6.4 cm than at 8.9 cm, which were almost exactly the same as our X_2 and X_3 locations at 6.40 and 8.94 cm. In other words, our data are consistent with the Nikolaev *et al*. data [Nikolaev, 2000] in terms of the mirror placement.

We attempted to isolate the major trends with the data presented in the following sections. In general, the trends were similar for all of the sets of hardware except as noted below. Most experiments focused on the X_2 optical axis position at 6.4 cm based upon data shown in Figs. 15 and 16.

3.3.2 Ejector Flow Effects on Laser Performance and Pressure

One of the early questions that needed to be answered was the performance of the configuration as a function of ejector flow rate. Using N_2 diluent in the SOG, the ejector flow rate was varied for the cylindrical ejectors at two different optical axis locations, Fig. 17. At the X_2 location, the highest performance was observed with an ejector flow rate in the range of 200-300 mmol/s. Interestingly, at the X_1 position the highest performance was observed with higher ejector flow rates of around 550 mmol/s; this was unexpected, but may be a result of enhanced mixing further upstream with higher ejector flow rates. Note that the data in Fig. 17 seem to suggest that perhaps the X_1 position results in higher power (contrary to Fig. 15), but the data were taken with two different Cl_2 flow rates thereby resulting in a misperception. In fact, the peak chemical efficiency for the X_2 location is higher than that at X_1. Scarce data at the X_3 position indicate a similar trend to that at the X_2 position, i.e., the highest performance was observed with an ejector flow rate in the range of 200-300 mmol/s. Limited range scans of performance for the cylinders and starlet ejectors for both N_2 and He roto-SOG diluent supported these trends.

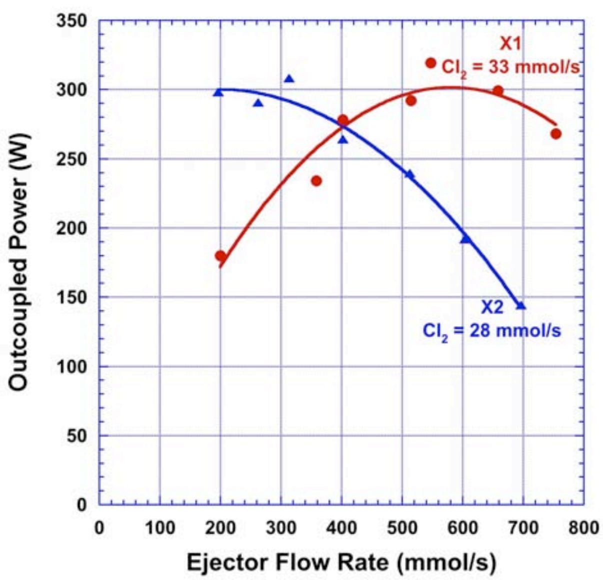

Figure 17: Outcoupled laser power versus N_2 ejector flow rate when using the cylindrical ejectors and N_2 diluent in the roto-SOG.

The trend in performance versus ejector flow rate has a different character when using the conical starlet ejectors, Figs. 18 and 19. A more complete examination was performed for these ejectors because of their higher pressure recovery potential. For the conical starlets, the laser performance peaked at a higher ejector flow of 500 mmol/s at the X_2 (6.4 cm) optical axis location. The performance begins to drop off beyond 550 mmol/s, but it is difficult to determine for sure if the lack of a bank blower aero window-diffuser section is allowing a normal shock to propagate into the laser cavity region. *Integrated hot-fire experiments with a well-integrated diffuser section would have to be performed to properly determine the answer to this question*.

Hot fire experiments showed only a minimal change in generator pressure as ejector flow is added, Fig. 20. *This suggests a significant advantage to this ejector nozzle configuration in that it is possible to operate the system with existing high efficiency SOGs operating in the 40-70 Torr range while at the same time maintaining high-pressure recovery potential via the ejector nozzle concept* [Nikolaev, 2000; Zagidullin, 2001]. Figure 21 shows the rise in the pressure in the laser cavity as a function of the ejector flow rate for the conical starlets. Laser cavity pressures with the sonic starlets and cylindrical ejectors were approximately 35% larger as a function of ejector flow rate (not shown for brevity) than those shown in Fig. 21 with the Mach 2 conical starlet ejectors.

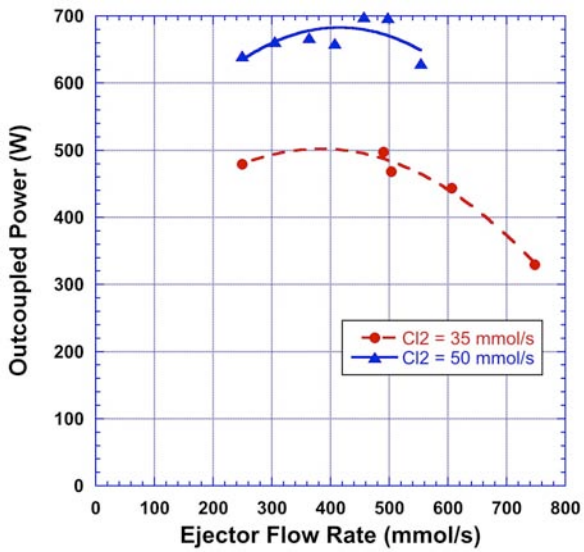

Figure 18: Outcoupled laser power versus N_2 ejector flow rate when using the conical starlet ejectors for two Cl_2 flow rates and approximately a 1:1 diluent ratio of He diluent in the roto-SOG.

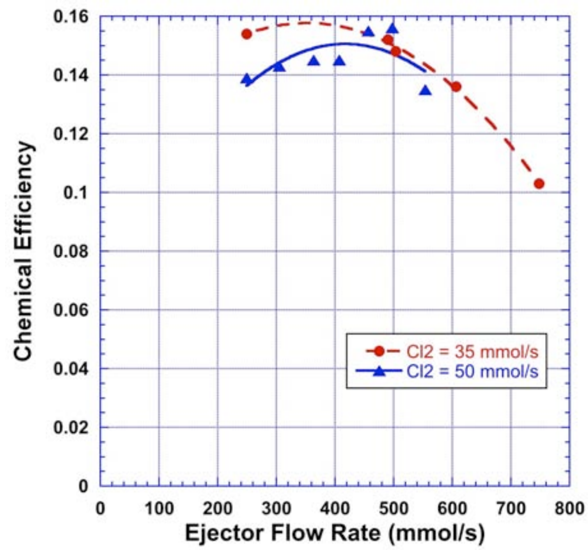

Figure 19: Chemical efficiency versus N_2 ejector flow rate when using the conical starlet ejectors for two Cl_2 flow rates and approximately a 1:1 diluent ratio of He diluent in the roto-SOG.

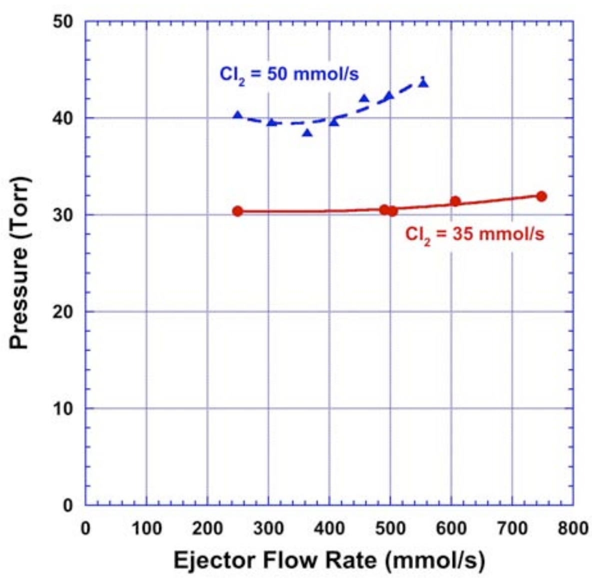

Figure 20: SOG pressure versus N_2 ejector flow rate when using the conical starlet ejectors for two Cl_2 flow rates and approximately a 1:1 diluent ratio of He diluent in the roto-SOG.

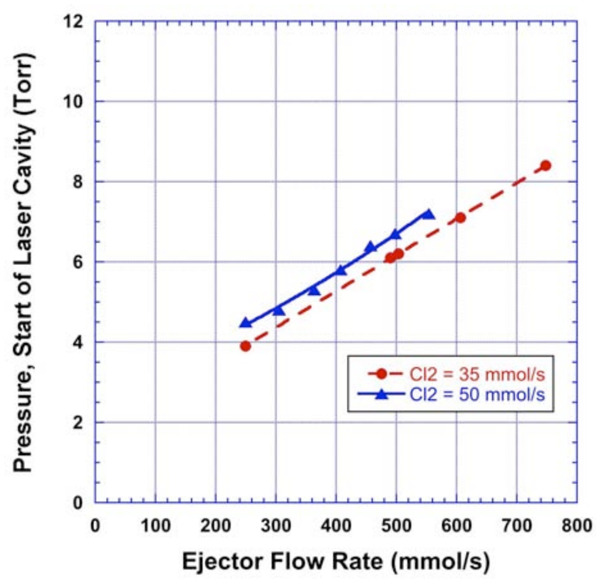

Figure 21: Nozzle pressure at leading edge of laser cavity vs. N_2 ejector flow rate when using the conical starlet ejectors for two Cl_2 flow rates and approximately a 1:1 diluent ratio of He diluent in the roto-SOG.

3.3.3 Iodine Flow Rate Effect on Laser Performance

Figures 22 and 23 show the outcoupled laser power as a function of iodine flow rate and the corresponding titration ratio, respectively, for the starlet ejectors at a chlorine flow rate of ~32 mmol/s. Generally, the favored titration ratio (equal to the ratio of the I_2 flow rate to the total O_2 flow rate) was around 2.3%, but it tended to be lower for subsequent higher-Cl_2-flow rate tests.

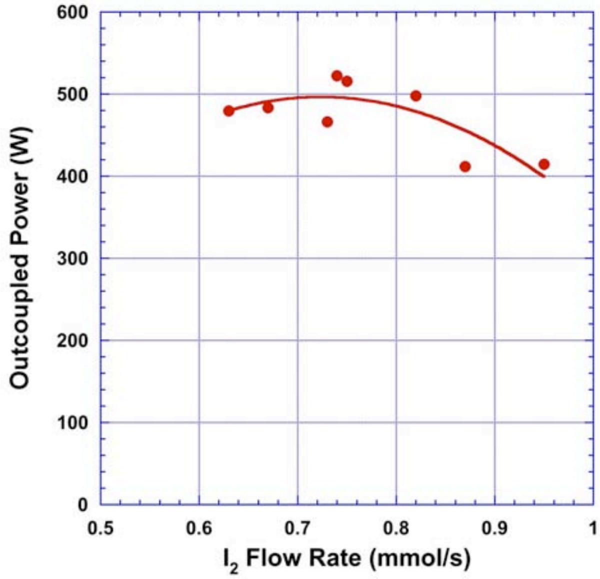

Figure 22: Outcoupled laser power versus I_2 flow rate when using the starlet ejectors. The Cl_2 flow rate was ≈ 32 mmol/s buffered with ≈ 35 mmol/s of He diluent in the roto-SOG.

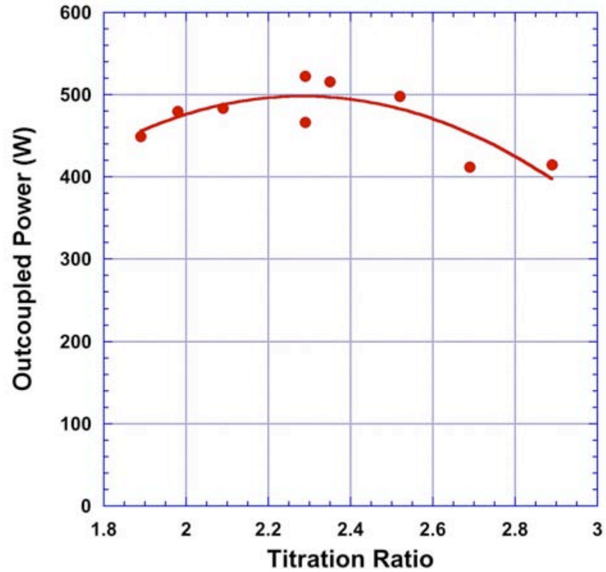

Figure 23: Outcoupled laser power versus titration ratio when using the starlet ejectors. The Cl_2 flow rate was ≈ 32 mmol/s buffered with ≈ 35 mmol/s of He diluent in the roto-SOG.

3.3.4 Primary Diluent Flow Rate Effect on Laser Performance

Using the ejector nozzle concepts, the optimal diluent ratio was found to be lower than with the VertiCOIL nozzle, though fairly insensitive in general. For the VertiCOIL nozzle, the optimum diluent ratio was typically 3:1 – 4:1 with helium diluent and 2:1 – 3:1 with nitrogen diluent. Data taken with the conical starlet ejectors showed little sensitivity to nitrogen, but some sensitivity with helium diluent with an optimum in the 1:1 – 2:1 range, Fig. 24. With the starlet ejectors the diluent ratio with helium was relatively insensitive over the range of flow rates explored, Fig. 25. Typically a diluent ratio (equal to the ratio of the diluent flow rate to the Cl_2 flow rate) of approximately 1:1 was run for other flow conditions.

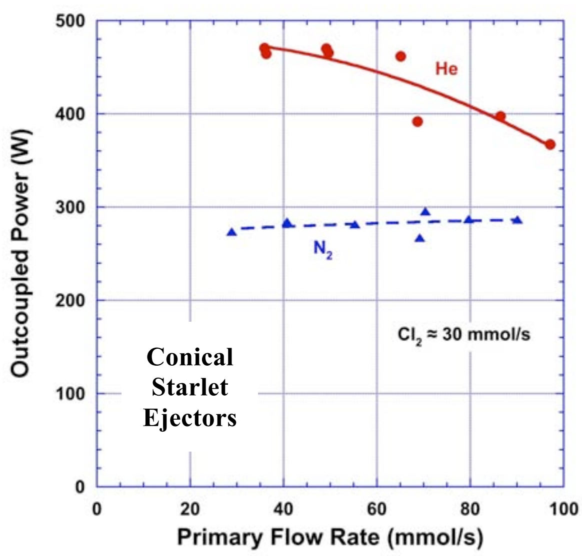

Figure 24: Outcoupled laser power versus primary flow rate when using the conical starlet ejectors. The Cl_2 flow rate was ≈ 30 mmol/s.

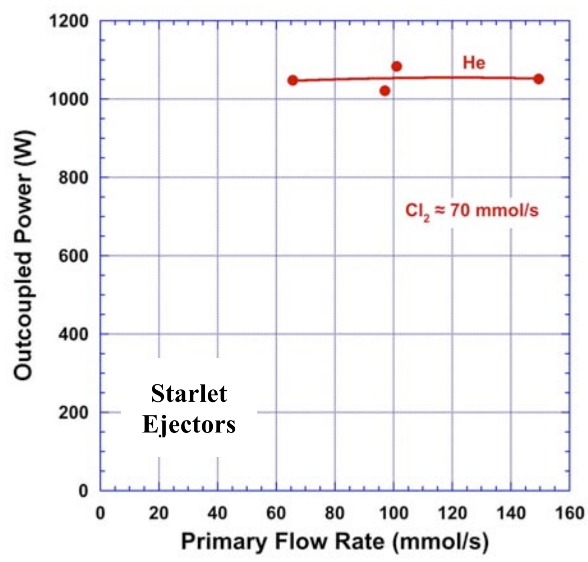

Figure 25: Outcoupled laser power versus primary He flow rate when using the starlet ejectors. The Cl_2 flow rate was ≈ 70 mmol/s.

3.3.5 Gain Measurements and Estimates

Very limited gain data were taken in order to focus on laser performance of the many configurations. A sample of the gain data is shown in Fig. 26 and shows a measured gain of 0.62 % cm^{-1} for helium diluent and 0.56 % cm^{-1} for nitrogen diluent. We also acquired a limited amount of power versus reflectivity data from which the small signal gain can be estimated by extrapolating the power versus reflectivity data to zero outcoupled power, e.g., Fig. 27. A comparison of gain measurements versus location from the ejector plane and the type of ejector are shown in Figs. 28 and 29. In general, the gain with starlets was slightly higher than that with cylinders, and both were higher than the conical starlet ejectors. It is recommended that more detailed gain data be taken in the future.

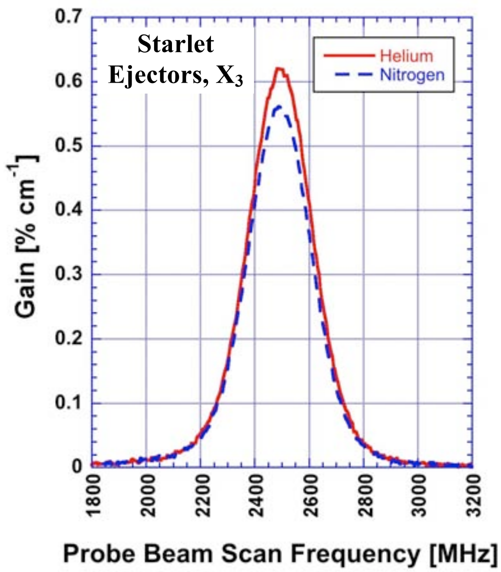

Figure 26: Grain profiles when using the starlet ejectors as a function of type of diluent in the roto-SOG. Optical axis located at the X_2 position, 6.40 cm downstream from the ejector exit plane. The Cl_2 flow rate was 31 mmol/s.

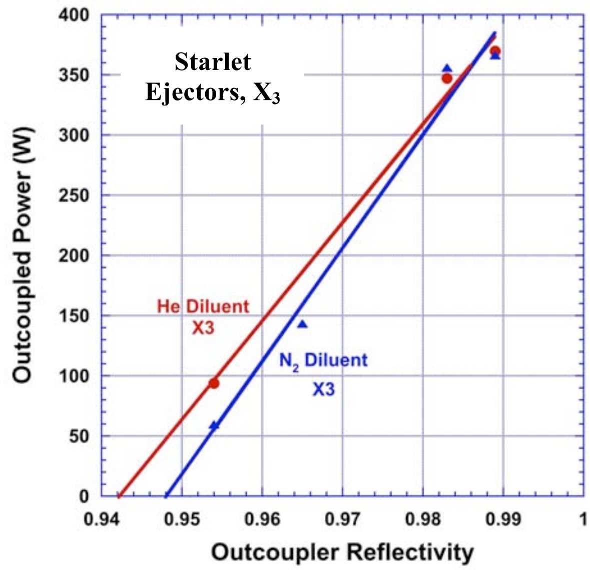

Figure 27: Outcoupled laser power versus outcoupler reflectivity when using the starlet ejectors as a function of type of diluent in the roto-SOG. Optical axis located at the X_3 position, 8.94 cm downstream from the ejector exit plane. The Cl_2 flow rate was 31 mmol/s.

In general, the magnitude of our gain measurements (approximately 0.62 % cm^{-1}) is consistent with those of other research groups [Nikolaev, 2002]. However, Nikolaev *et al*. observed a higher peak gain of approximately 0.70 % cm^{-1}. We believe that this is primarily a consequence of our earlier observation that the VertiCOIL nozzle performance data indicated that we might expect a 4-5 percentage point drop in chemical efficiencies because of the use of the old roto-SOG design combined with a lower molarity limitation (due to limited bulk availability of higher concentration H_2O_2) on our BHP mixture; correspondingly we should also anticipate lower small signal gains.

A trend that was different between our data and that of Nikolaev *et al*. was that we observed lower gain further upstream, whereas their peak gains occurred in their furthest upstream measurement position of 4.25 cm. It is possible that our measurement at 3.86 cm was just far enough upstream to show a significant drop in gain, but a more likely explanation is that the two data points shown at 3.86 cm in Figs. 28 and 29 were extrapolated from laser power versus reflectivity curves. As discussed above, because the laser power measurement at the X_1 position includes the flow stretching all the way into the less well-mixed region 1.4 – 2 cm from the ejector exit plane, the laser power was lower and correspondingly the small signal gain number extracted from such data may be significantly in error. As such, we will not examine this discrepancy any further and simply state that more data with the small signal gain diagnostic is recommended in future studies.

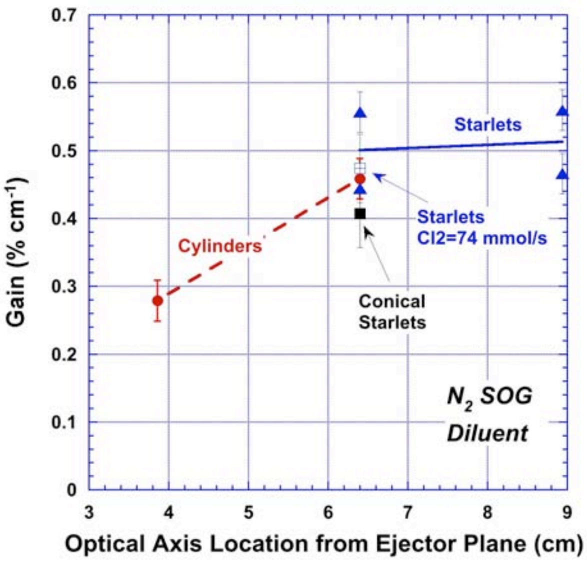

Figure 28: Gain versus the position of the optical axis from the ejector plane when using cylindrical, starlet, and conical starlet ejectors. The Cl_2 flow rate was ≈ 30 mmol/s buffered with ≈ 30 mmol/s of N_2 diluent in the roto-SOG.

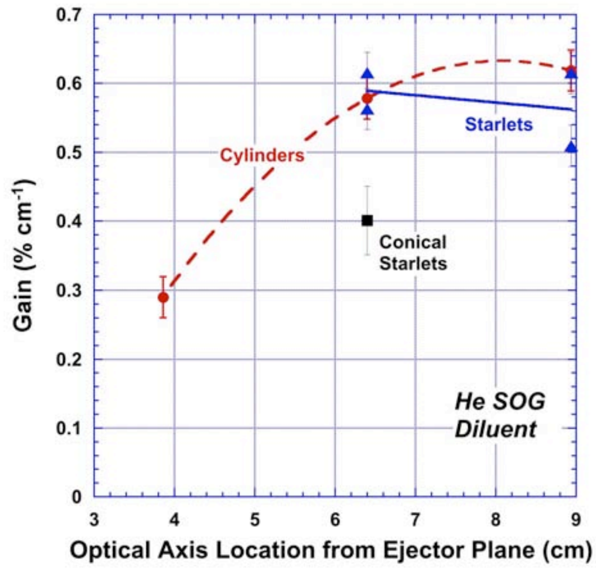

Figure 29: Gain versus the position of the optical axis from the ejector plane when using cylindrical, starlet, and conical starlet ejectors. The Cl_2 flow rate was ≈ 30 mmol/s buffered with ≈ 30 mmol/s of He diluent in the roto-SOG.

3.3.6 Chlorine Flow Rate Effect on Laser Performance

A summary of the data in terms of outcoupled power and chemical efficiency as a function of chlorine flow rate is shown in Figs. 30 and 41. Several important points can be made from these figures:

1) *One of the most important observations to make is that the innovative "starlet" design (the major focus of this entire program) significantly outperformed the cylindrical ejectors by typically 20-30% in terms of outcoupled power for the same Cl_2 flow rate and an equivalent of about 4-5 percentage points of chemical efficiency.*
2) The starlets with I_2 injector tubes pointed directly downstream outperformed the starlets when the I_2 injector tubes were rotated in towards the $O_2(^1\Delta)$ slots by 45°. This result is consistent with Russian data where the I_2 injector tubes were rotated by 90° and also resulted in worse performance [Hager, 2003].
3) The conical starlet ejector configuration also performed significantly better than the cylindrical ejectors by typically around 15% in terms of outcoupled power for the same Cl_2 flow rate and an equivalent of about 1.5 percentage points of chemical efficiency. This finding supports two important hypotheses from the PLIF measurements [Ragheb, 2010a]: *(i) that the starlet design significantly improves mixing (as demonstrated by the cold flow PLIF experiments), even for the much higher speed conical ejectors, and (ii) that there are designs that enhance the mixing significantly for cases with very high pressure recovery potential.*
4) The VertiCOIL nozzle performance data indicated that we might anticipate a 4-5 percentage point drop in chemical efficiencies because of the use of the old roto-SOG design combined with a lower molarity limitation (due to limited bulk availability of higher concentration H_2O_2) on our BHP mixture. Fig. 30 shows that we were obtaining chemical efficiencies of around 14-15% with the cylindrical ejectors, whereas the Russian data [Nikolaev, 2000] was typically 19-20% for a similar cylindrical ejector geometry; this confirms our initial estimation that our data would be quantitatively lower than the Russian numbers.

We suggest that with a more advanced SOG and a higher molarity BHP mixture that the starlet and conical starlet ejectors concepts could achieve chemical efficiencies of approximately 24% and 21%, respectively. These numbers are consistent with more recent variations of the ejector nozzle concept in Russian experiments [Zagidullin, 2005; Hager, 2003].

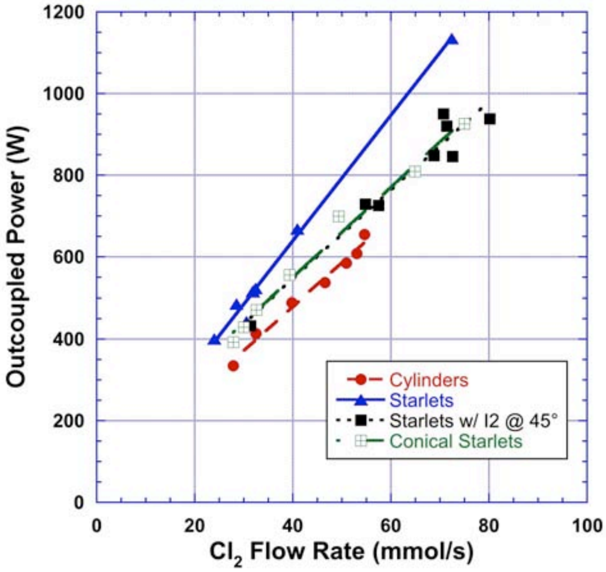

Figure 30: Outcoupled laser power versus Cl_2 flow rate when using the four different ejector geometries (cylinders, starlets, starlets with I_2 injectors rotated 45°, and conical starlets) and approximately a 1:1 diluent ratio of He in the roto-SOG.

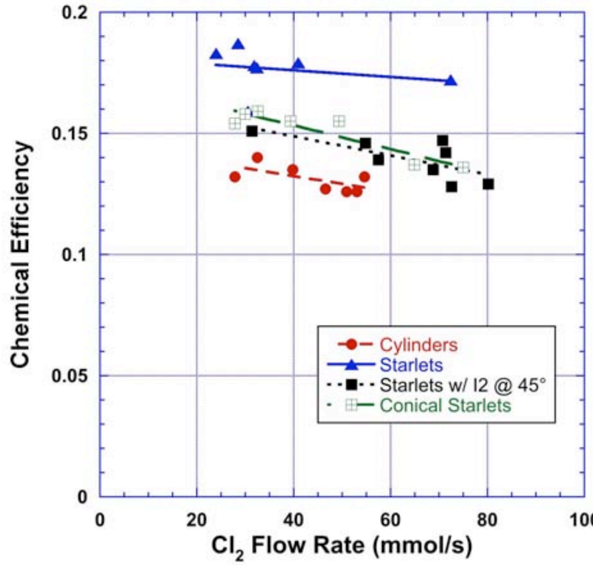

Figure 31: Chemical efficiency versus Cl_2 flow rate when using the four different ejector geometries (cylinders, starlets, starlets with I_2 injectors rotated 45°, and conical starlets) and approximately a 1:1 diluent ratio of He in the roto-SOG.

IV. Concluding Remarks

This effort explored the feasibility of an innovative iodine mixing and pressure recovery nozzle-ejector "Starlet" concept. The results of the research relate (connect) the data from the nozzle-ejector concept to the database with VertiCOIL-type lasers, and lay the foundation for developing a highly advanced COIL ejector-mixing nozzle. One of the most important findings was that the innovative "starlet" ejector design (the major focus of this program) significantly outperformed the cylindrical ejectors by typically 20-30% in terms of outcoupled power for the same Cl_2 flow rate and an equivalent of about 4-5 percentage points of chemical efficiency. The conical starlet ejector configuration also performed significantly better than the cylindrical ejectors by typically around 15% in terms of outcoupled power for the same Cl_2 flow rate and an equivalent of about 1.5 percentage points of chemical efficiency. This finding supports two important hypotheses from the PLIF measurements: *(i) that the starlet design significantly improves mixing (as demonstrated by the cold flow PLIF experiments) even for the much higher speed conical ejectors, and (ii) that it is an especially important approach to enhance the mixing significantly for cases with very high pressure recovery potential* (for brevity here, pressure recovery will be the subject of another paper). The detailed PLIF measurements and quantitative analysis [Ragheb, 2010a] confirmed that the injection geometry strongly affects mixing, with the following trends discernible: (a) using smaller size ejectors (small cylinders vs. large cylinders, small starlets vs. large starlets) results in better mixing, and (b) *adding starlets to a given ejector geometry results in better mixing (particularly prominent for the conical ejectors)*. Overall, small starlets produce the best mixing, closely followed by small cylinders. Conical ejectors produced the poorest mixing, but conical ejectors with starlets (conical starlets) produced reasonably fast mixing and had the highest pressure recovery potential. *There appears to be a significant advantage to this ejector nozzle configuration in that it may be possible to operate the system with existing high efficiency SOGs operating in the 40-70 Torr range while at the same time obtaining high-pressure recovery potential via the ejector nozzle concept. This should enable one to operate this concept with high efficiency SOG designs without adversely affecting the generator performance, and without requiring a special high pressure SOG design*.

The VertiCOIL nozzle performance data indicated that we might expect a 4-5 percentage point drop in chemical efficiencies because of the use of the old roto-SOG design combined with a lower molarity limitation (due to limited bulk availability of higher concentration H_2O_2) on our BHP mixture. We were obtaining chemical efficiencies of around 14-15% with the cylindrical ejectors, whereas the Russian data [Nikolaev, 2000] was typically 19-20% for a similar cylindrical ejector geometry; this confirms our initial projection that our data would be quantitatively lower than the Russian numbers (which were obtained with high molarity BHP). *We expect that with* *a more advanced SOG and a higher molarity BHP mixture that the starlet and conical starlet ejectors concepts will achieve chemical efficiencies of approximately 24% and 21%, respectively*. These numbers are consistent with more recent variations of the ejector nozzle concept in Russian experiments [Zagidullin, 2005].

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