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Performance of a Multistream Injection Chemical Oxygen–Iodine Laser with Starlet Ejectors

Darren M. King,* David L. Carroll,† Tyler H. Field,‡ Julia K. Laystrom-Woodard,§
Richard J. Driscoll,¶ and Lee H. Sentman**
CU Aerospace, Champaign, Illinois 61820
and
Adam M. Ragheb,†† Gregory S. Elliott,‡‡ and Wayne C. Solomon§§
University of Illinois at Urbana–Champaign, Urbana, Illinois 61801

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A variant of an ejector-mixing nozzle for a chemical oxygen–iodine laser was experimentally tested with notched starlet ejectors. Cold-flow planar laser-induced fluorescence measurements indicated 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. Furthermore, a conical ejector design with starlet notches was 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 were relatively constant with ejector flow rate, suggesting that existing high-efficiency singlet-oxygen generators 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 [1]. Since that initial demonstration, COIL technology has undergone numerous improvements [2–5]; chemical efficiencies as high as 36–40% using nitrogen diluent have been demonstrated [6]. 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. Downstream of the chemical SOG are two critical multidisciplinary aerospace technology elements, the gas mixing nozzle, and the gas ejector pressure recovery system. It has long been understood that mixing of the gaseous molecular iodine with the singlet oxygen and subsequent dissociation of the iodine play a critical role in COIL performance [2,4–10], but much of the work to date 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) [11].

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 et al. [12,13] and Yang et al. [14] with ejector-mixing nozzles, along with detailed modeling [15–17], 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 [12] appears particularly promising, and the design evolved through later work over several years [18–21]. 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 [22]. Pannu and Johannesen reported results on a series of experiments concerning sonic flow from tubes with V-shaped slots cut into the ends. Our interest in these experiments concerns the flowfield 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 [23], 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¶¶ is a variant design of the source flow ejector-mixing nozzle studied by Nikolaev et al. [12,13], 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 played a major role in the evolution of the starlet nozzle design.

The VertiCOIL system [24–26] with roto-SOG serves as our baseline point of departure for the more advanced work conducted herein. The VertiCOIL system is well characterized in terms of laser performance with both helium and nitrogen diluent. The University of Illinois at Urbana–Champaign (UIUC) 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.).

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. [24] and Carroll

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*Laboratory Manager, 301 N. Neil Street, Suite 400. Senior Member AIAA.
†President, 301 N. Neil Street, Suite 400. Fellow AIAA.
‡Staff Engineer, 301 N. Neil Street, Suite 400.
§Senior Engineer, 301 N. Neil Street, Suite 400.
¶Senior Consultant, 301 N. Neil Street, Suite 400. Associate Fellow AIAA.
**Senior Consultant, 301 N. Neil Street, Suite 400. Fellow AIAA.
††Graduate Research Assistant, 104 S. Wright. Student Member AIAA.
‡‡Professor, 104 S. Wright. Associate Fellow AIAA.
§§Professor Emeritus, 104 S. Wright. Fellow AIAA.

¶¶D. L. Carroll and W. C. Solomon, private communication, 7 October 2005.

et al. [25]. The CU Aerospace (CUA) and UIUC team updated, upgraded, and reconfigured the existing COIL (VertiCOIL) hardware for the lasing experiments detailed in Sec. III.

A schematic of the VertiCOIL test bed is shown in Fig. 1. 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, were also updated to accommodate new demands. Details of the VertiCOIL hardware can be found in [24,25].

Cold-flow planar laser-induced fluorescence (PLIF) and schlieren testing [27,28] on a smaller hardware setup were performed for several different ejector sets: 1) small cylindrical ejectors having a diameter of 1.473 mm, 2) small cylindrical ejectors with the notched starlets, 3) large cylindrical ejectors having a diameter of 2.210 mm, 4) large cylindrical ejectors with the notched starlets, 5) conical ejectors with a geometric area corresponding to a Mach 2 exit flow, and 6) Mach 2 conical ejectors with notched starlets at the exit. (Note that PLIF results from the first two and latter two configurations are shown in Sec. III.A.) The results of the PLIF testing [27,29] 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 showed 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, we downselected to three ejector sets for hot-fire testing: 1) small cylindrical ejectors, 2) small cylindrical ejectors with starlets, and 3) conical ejectors with starlet notches at the exit.

A variety of Micro Motion CMF and Omega FMA mass flow meters were used to measure the flow rates of the gases, including the gaseous I_2. Pressures reported here in the subsonic and supersonic flow regions were measured by capacitance manometers from MKS and Leybold. Power transmitted through the outcoupling mirror was measured with an Ophir 5000W-CAL-SH power meter. The power meter calibration was verified using a constant voltage-constant current power source. In general, the accuracy of the measurements was within 1% of the stated value and, unless otherwise noted, the error bars on the data fall within the size of the data point itself.

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 12.70×26.67 cm openings for the simple, rapid installation of multiple nozzle concepts; see Fig. 2. 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.

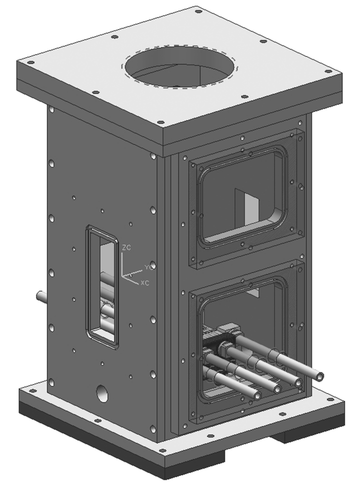

Fig. 2 Hot-fire hardware installed in laser cavity housing.

Figure 3 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; see Figs. 4 and 5. A fourth configuration that also received limited testing was one in which the I_2 injector tubes were rotated 45° to point in toward the $O_2(^1\Delta)$ flow at an angle (normally, the I_2 injectors were

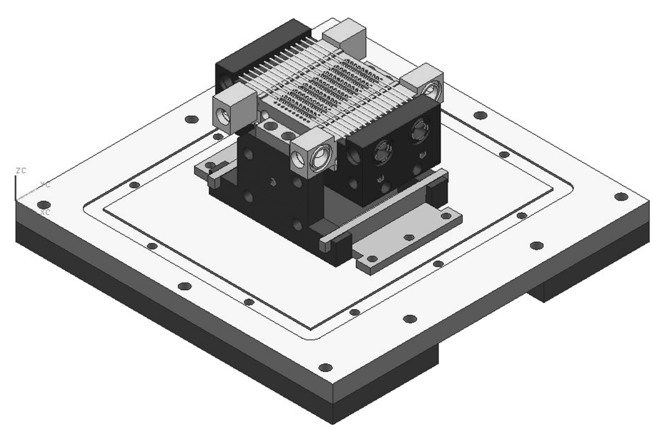

Fig. 3 Hot-fire hardware attached to bottom wall.

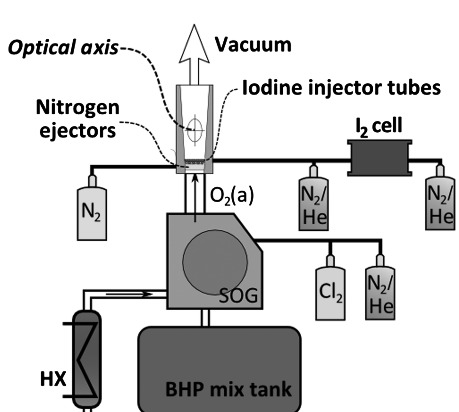

Fig. 1 Schematic of COIL device elements shown with new ejector nozzle (not to scale) (HX denotes heat exchanger).

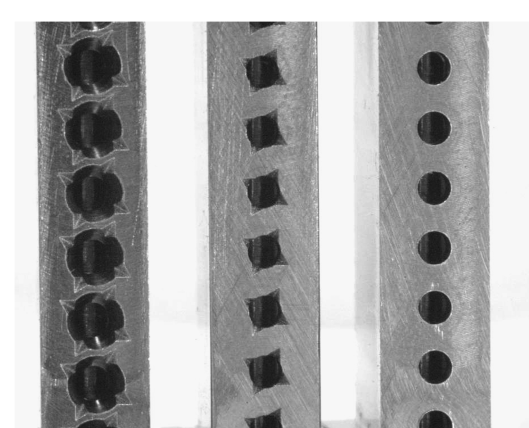

Fig. 4 All three ejector nozzle concepts: conical starlets (left), small cylindrical starlets (center), and small cylinders (right).

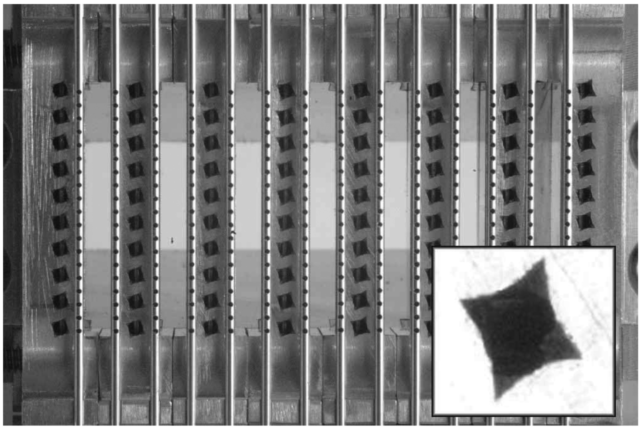

Fig. 5 CUA–UIUC advanced starlet (see inset) ejector nozzle hot-fire hardware.

directed in the flow direction); this test was only performed with the small starlet ejectors.

Although the mirror-duct-to-cavity fixture is static, a translation of the final optic mount in the flow direction permits slightly greater than 6.35 cm of adjustment in the optical axis downstream of the iodine injection plane. 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. The pressure in the lasing cavity was approximately constant with the expansion ramps installed. More details of the starlet laser hardware can be found in King et al. [30].

III. Experimental Results

A. Planar Laser-Induced Fluorescence Experiments with Conical and Conical Starlet Ejectors

The PLIF setup centered on a Quantel Brilliant B neodymium-doped–yttrium-aluminum-garnet laser capable of producing 450 mJ of energy per pulse at 532 nm; the laser pulses at a frequency of 10 Hz. Images are acquired with an Andor iStar intensified charge-coupled device (CCD) camera, with a generation 3 intensifier having a quantum efficiency of approximately 50% at the 532 nm wavelength. To remove the background laser sheet from the fluorescence images, a Kintek holographic notch filter was used, which had an optical density of greater than 6.0 at 532 nm. The lens used on the Andor camera for horizontal PLIF was a Nikon Nikkor 85 mm lens, with an f number of 1.4, while a Nikkor perspective-correcting lens with an f number of 2.8 was used for vertical PLIF imaging; this lens allowed for the camera to record undistorted images of a vertical plane while not oriented perpendicular to the plane. The lens was adjusted by placing a dotcard at the location of the laser plane and manually adjusting the lens so that the dots were evenly spaced and all in focus on the computer screen output of the CCD camera. PLIF images were recorded in the tagged image file format in two 50-image stacks (later combined into a single 100-image stack), while only one 50-image stack was recorded for the background images. Image processing was performed in MATLAB. The N_2 ejector flow rate was varied (Fig. 6), while the slot flow rate was held at 32.1 mmol/s of N_2 and the iodine injectors contained a mixture of 6.9 mmol/s of N_2 and 0.030 mmol/s of I_2. To insure as consistent an I_2 flow rate as possible from one experiment to the next, the iodine sublimation cell was always set to 70°C, the iodine lines and injector blocks were set to 100°C, and the I_2 was allowed to flow for at least 1 min until the measured flow rate had stabilized; these temperatures at a relatively small I_2 flow rate prevented any plugging or buildup of iodine, and we estimate our error in I_2 flow rate in these experiments to be $\pm 2\%$. A more detailed description of the PLIF experimental setup for these smaller-scale (only four columns of ejectors) cold-flow tests is provided in Ragheb et al. [27].

The PLIF series of Ragheb et al. [27] was completed by testing 1) conical ejectors with a geometric area corresponding to a Mach 2 exit flow, and 2) Mach 2 conical ejectors with notched starlets at the exit; see Fig. 6. For brevity, only the location nearest the ejector plane (1.27 cm downstream) is shown in Fig. 6 in a comparison between small cylinders, small starlets, conical ejectors, and conical starletted ejectors. Images for the small cylinders and small starlets were presented in Ragheb et al. [28], and images for the conical and conical starlet ejectors are new to this work. 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

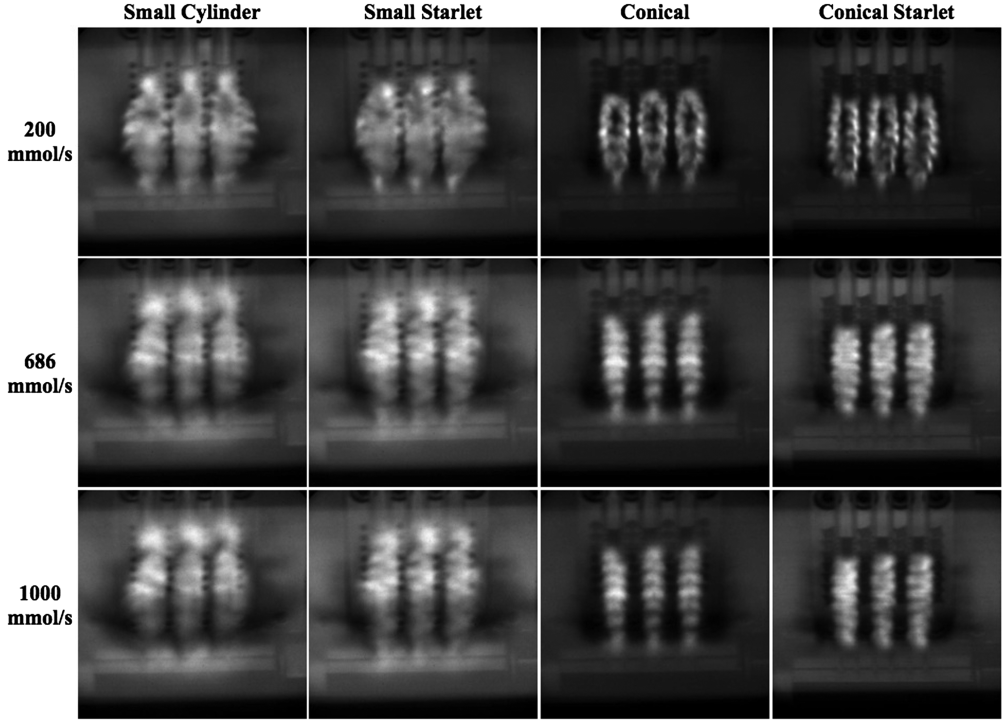

Fig. 6 PLIF imaging experiments with small-scale cold-flow hardware, detailed in Ragheb et al. [27], comparing four ejector geometries, including the conical starlets (far right column) at three ejector flow rates.

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. Visually, the small cylinders and small starlets appear similar from a mixing perspective; a detailed quantitative histogram analysis by Vorobieff et al. [29] showed that the small starlets do indeed have approximately a 5–10% enhancement in mixing. 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, there is faster mixing taking place with the conical starlets.

B. 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-SOG, 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. These data were consistent with prior data taken by Carroll et al. [25] with the VertiCOIL system using a 6.6 M HO_2–BHP mixture. Essentially identical laser performance was also verified using the new laser cavity housing; see Fig. 2.

A black 1.27-cm-thick acrylic sheet was cut into 10.16×10.16 cm 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 typical burn block taken over a laser-on period of 3 s had a near-field beam size of 2.2×3.1 cm for a 1050 W laser beam. Remote video capability was added using a TRENDnet TV-IP410 CCD camera.

An interesting finding was that it was possible to observe the outcoupled laser beam shape on the face of the power meter; see Fig. 7. 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.

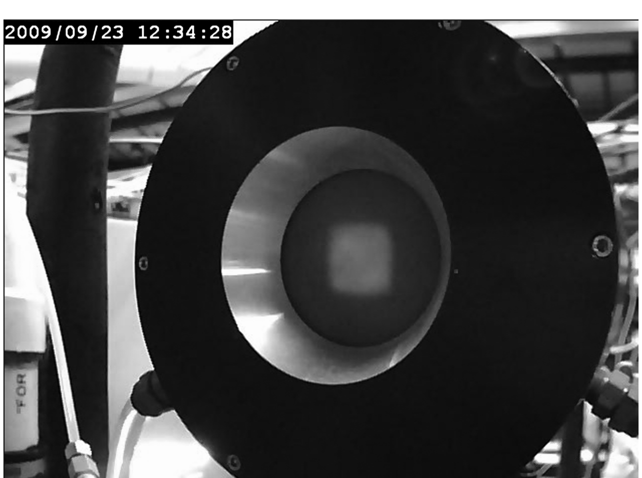

Fig. 7 Infrared laser beam viewed remotely by a TRENDnet TVIP410 pan/tilt internet CCD camera on the water-cooled 5 kW Ophir 5000W-CAL-SH thermopile power meter.

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 M. This results in lower Cl_2 utilizations and $O_2(^1\Delta)$ yields from our roto-SOG as compared with the U.S. Air Force Research Laboratory VertiCOIL data taken by Rittenhouse et al. [24], in which 70% H_2O_2 was used in mixtures to generate 7.5 M BHP. Comparing the preceding experimental data and the data from [25] with that of [24] indicates that the resulting performance penalty is historically approximately four percentage points of chemical efficiency; for example, Rittenhouse et al. [24] reported 27% chemical efficiency with He diluent, whereas we obtained 23%. Similarly, the peak gain measured by Keating et al. [26] with 70% H_2O_2 was 1.67% cm^{-1} versus 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 four to five 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 M BHP [21]. 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.

C. Ejector Nozzle Performance

Because of 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 (Sec. III.C.1), ejector flow rate (Sec. III.C.2), I_2 flow rate (Sec. III.C.3), primary diluent flow rate (Sec. III.C.4), gain (Sec. III.C.5), power, and chemical efficiency as a function of Cl_2 flow rate (Sec. III.C.6).

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. The laser power results (not shown for brevity) indicated that, for all configurations, the best position to locate the optical axis is approximately at $X_2 = 6.40$ cm. These data are consistent with the Nikolaev et al. [12] mirror position data.

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 next. Most experiments focused on the X_2 optical axis position at 6.4 cm.

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; see Fig. 8. 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. 8 seem to suggest that perhaps the X_1 position results in higher power (contrary to the findings discussed in Sec. III.C.1), 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

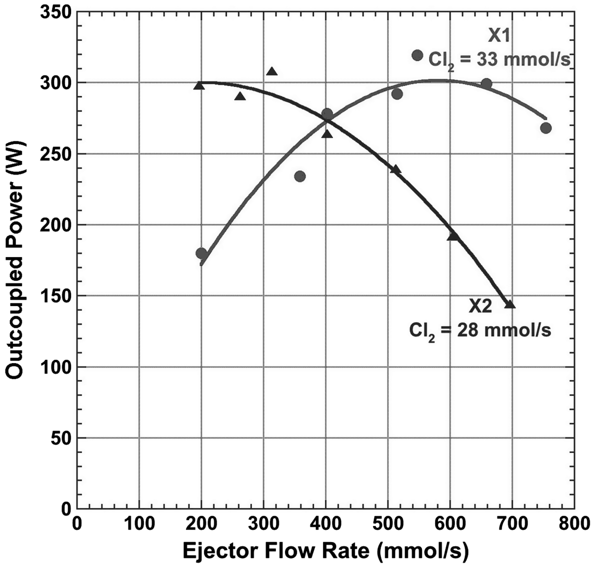

Fig. 8 Outcoupled laser power vs N_2 ejector flow rate when using the cylindrical ejectors and N_2 diluent in the roto-SOG.

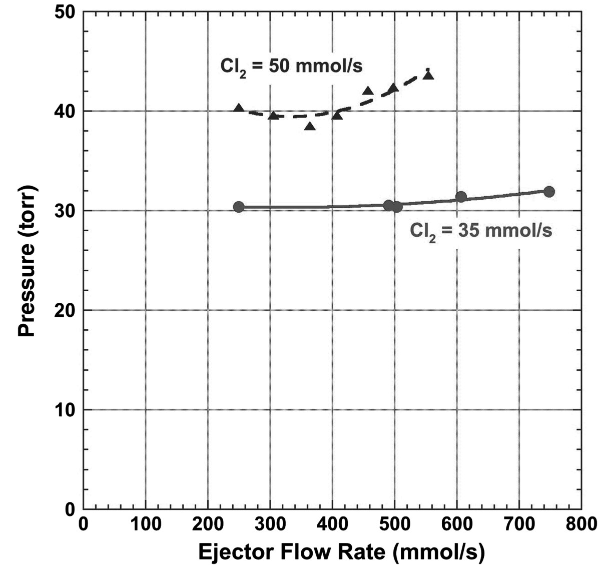

Fig. 10 SOG pressure vs N_2 ejector flow rate when using the conical starlet ejectors for two Cl_2 flow rates and an approximately 1:1 diluent ratio of He diluent in the roto-SOG.

X_2 position; that is, 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.

The trend in performance versus ejector flow rate has a different character when using the conical starlet ejectors; see Fig. 9. 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. Corresponding chemical efficiencies are in the 14–16% range for ejector flows less than 550 mmol/s. 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; see Fig. 10. 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 [12,18]. Figure 11 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% higher as a function of ejector flow rate (not shown for brevity) than those shown in Fig. 11 with the Mach 2 conical starlet ejectors.

3. *Iodine Flow Rate Effect on Laser Performance*

Figure 12 shows the outcoupled laser power as a function of iodine flow rate for the starlet ejectors at a chlorine flow rate of ~32 mmol/s. The corresponding 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.

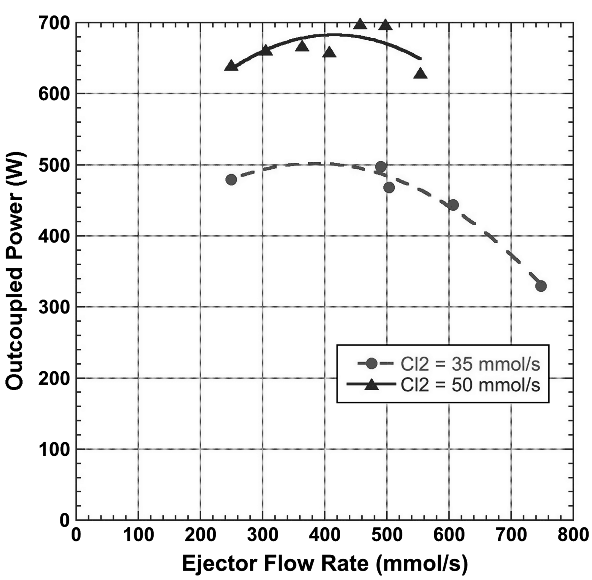

Fig. 9 Outcoupled laser power versus N_2 ejector flow rate when using the conical starlet ejectors for two Cl_2 flow rates and an approximately 1:1 diluent ratio of He diluent in the roto-SOG.

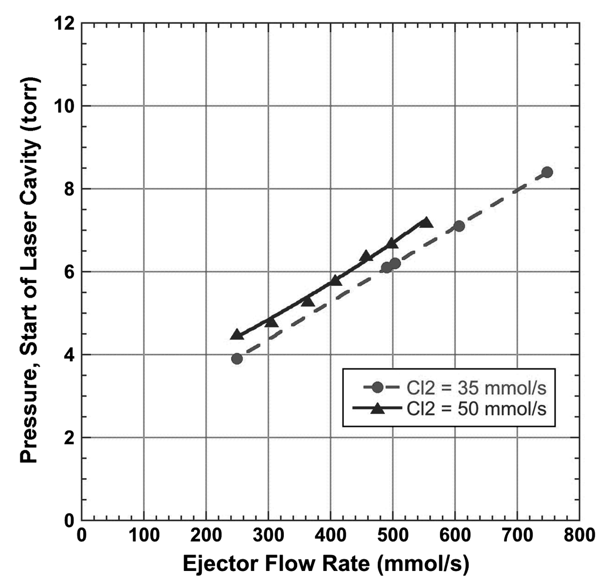

Fig. 11 Nozzle pressure at leading edge of laser cavity vs N_2 ejector flow rate when using the conical starlet ejectors for two Cl_2 flow rates and an approximately 1:1 diluent ratio of He diluent in the roto-SOG.

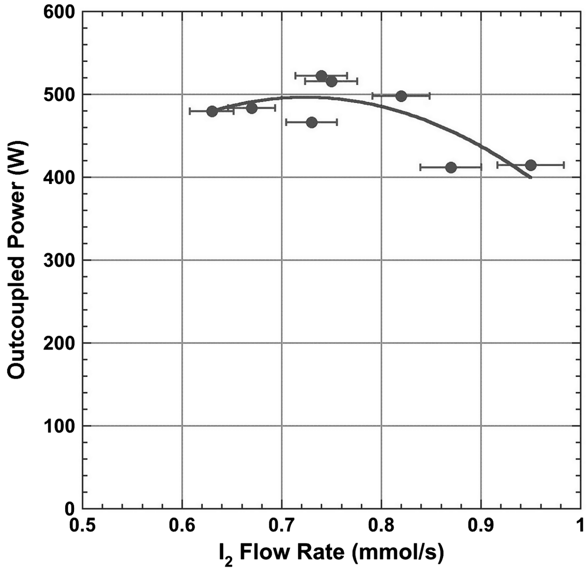

Fig. 12 Outcoupled laser power vs I_2 flow rate when using the starlet ejectors. The Cl_2 flow rate was ≈32 mmol/s buffered with ≈35 mmol/s of He diluent in the roto-SOG. The estimated error in these high-I_2 flow rate cases is ±3.5%.

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, although it is 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 [30]. With the starlet ejectors, the diluent ratio with helium was relatively insensitive over the range of flow rates explored [30]. 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.

5. Transition Blade Inserts Effect on Laser Performance

Because of concerns regarding flow obstruction in the presence of the ejector array inserts, 5.21-cm-long transition section blades (between the SOG and ejector plane) were added and tested in several hot-flow runs with the purpose of minimizing flow volume in the transition section, thereby minimizing pooling losses. A glass coating called Silcosteel®-CR (now Silcolloy™), provided by Restek (now Silcotek), was applied to the stainless blades to minimize singlet-delta surface deactivation. Laser power measurements were taken for several cases with the blades and, to within experimental error, were the same as when the blades were removed.

After three hot-fire test days, it was observed that the Restek glass coating had been completely eroded by reactions with BHP and/or singlet-delta oxygen. After the erosion, the blade surfaces were no longer smooth and were removed from further testing due to concerns that surface deactivation might outweigh any volume (residence time) losses of $O_2(^1\Delta)$. As such, further experiments were performed without the 5.21-cm-long transition blades in place. However, in lieu of the long blades, short 0.676-cm-long wedges were placed just upstream of the ejector inserts to guide the flow smoothly into the slots and minimize (or eliminate) any recirculation regions.

6. Gain Measurements

Very limited gain data were taken in order to focus on laser performance of the many configurations. Accurate measurements of gain were made using the iodine-scan diagnostic (ISD) [31] developed by Physical Sciences, Inc. The ISD is a diode-laser-based monitor for the small signal gain in iodine lasers. The system uses a single-mode tunable diode laser that is capable of accessing all six hyperfine components of the atomic iodine. It was calibrated in frequency for automated operation for the (3, 4) hyperfine transition for our experiments. A fiber-optic cable was used to deliver the diode laser probe beam to the supersonic laser cavity region. A typical measured gain for best performance conditions was 0.62% cm^{-1} for helium diluent and 0.56% cm^{-1} for nitrogen diluent in the SOG [30]. 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. 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.

In general, the magnitude of our gain measurements (approximately 0.62% cm^{-1}) is consistent with those of other research groups [13]. However, Nikolaev et al. [13] 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 four to five 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.

7. 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. 13 and 14.

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 four to five 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 toward 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 resulted in worse performance [20].

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

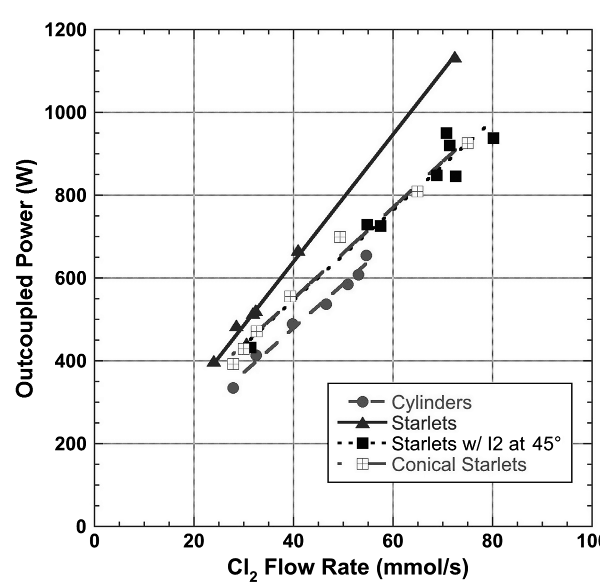

Fig. 13 Outcoupled laser power vs Cl_2 flow rate when using the four different ejector geometries (cylinders, starlets, starlets with I_2 injectors rotated 45°, and conical starlets) and an approximately 1:1 diluent ratio of He in the roto-SOG.

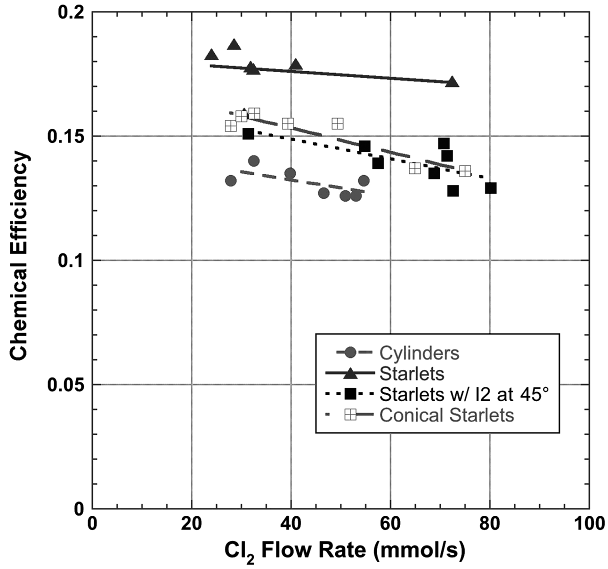

Fig. 14 Chemical efficiency vs Cl_2 flow rate when using the four different ejector geometries (cylinders, starlets, starlets with I_2 injectors rotated 45°, and conical starlets) and an approximately 1:1 diluent ratio of He in the roto-SOG.

finding supports two important hypotheses from the PLIF measurements [27]:

a) The starlet design significantly improves mixing (as demonstrated by the cold-flow PLIF experiments), even for the much higher speed conical ejectors.

b) These starlet designs enhance the mixing significantly for cases with very high pressure recovery potential.

4) The VertiCOIL nozzle performance data indicated that we might anticipate a four to five 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. Figure 14 shows that we were obtaining chemical efficiencies of around 14–15% with the cylindrical ejectors, whereas the Russian data [12] were 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, the starlet and conical starlet ejector 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 [20,21].

IV. Conclusions

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 starlet ejector design 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 four to five 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 earlier PLIF measurements and quantitative analysis [27,29]:

1) The starlet design significantly improves mixing (as demonstrated by the cold-flow PLIF experiments), even for the much higher speed conical ejectors.

2) It is an especially important approach to enhance the mixing significantly for cases with very high pressure recovery potential. It is noted that very little hardware geometry sizing optimization was performed during this work; it is possible that geometrical optimizations to further improve mixing (e.g., slot widths could be reduced and six notches could be used on the ejectors rather than four) may result in even larger performance increases at higher pressure operating conditions, but it is not possible to speculate by how much at this time without further experiments and/or detailed multidimensional modeling.

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 a four to five percentage point drop in chemical efficiencies might be expected 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 the BHP mixture presented in this paper. Chemical efficiencies of around 14–15% with the cylindrical ejectors were obtained, whereas the Russian data [8] were typically 19–20% for a similar cylindrical ejector geometry; this confirms the initial projection that the data would be quantitatively lower than the Russian numbers (which were obtained with high molarity BHP). It is expected that with a more advanced SOG and a higher molarity BHP mixture, the starlet and conical starlet ejector 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 [21].

Lastly, it is noted that this innovative starlet concept, in which notches are added to ejectors to enhance molecular mixing, could play an important role in improving mixing in other high-speed chemically reacting systems, including those relevant in combustion.

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R. Lucht
Associate Editor