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14. ABSTRACT

There are two important aspects to good injector performance in rocket engines—the atomization performance (droplet size and distribution, for example) and uniformity of operation (even distribution of droplets in time and space). In general, both of these aspects are affected by the geometry and operating conditions of the injector. In studying atomization performance, prior work has largely focused on the atomization performance, partially because uniformity, especially temporal uniformity, can be difficult to quantify. Attempts are made here to correlate the behavior of large-scale disturbances on the surface of the film with spray behavior. While correspondences were difficult to determine when comparing film video to by-eye observations of the spray, comparisons to spray video were more promising. High speed video of the spray showed a richness of behavior not observed with the naked eye. It also provides more quantitative data on nonuniformities, particularly the degree to which the spray and injector centerline are not aligned. Finally, comparisons of dominant frequencies in the spray and film show that upstream flow disturbances propagate downstream leading to spray nonuniformities. Overall a clearer understanding of spray nonuniformities is emerging.

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ATOMIZATION UNIFORMITY IN GAS-CENTERED SWIRL-COAXIAL INJECTORS

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ABSTRACT

There are two important aspects to good injector performance in rocket engines—the atomization performance (droplet size and distribution, for example) and uniformity of operation (even distribution of droplets in time and space). In general, both of these aspects are affected by the geometry and operating conditions of the injector. In studying atomization performance, prior work has largely focused on the atomization performance, partially because uniformity, especially temporal uniformity, can be difficult to quantify. Attempts are made here to correlate the behavior of large-scale disturbances on the surface of the film with spray behavior. While correspondences were difficult to determine when comparing film video to by-eye observations of the spray, comparisons to spray video were more promising. High speed video of the spray showed a richness of behavior not observed with the naked eye. It also provides more quantitative data on nonuniformities, particularly the degree to which the spray and injector centerline are not aligned. Finally, comparisons of dominant frequencies in the spray and film show that upstream flow disturbances propagate downstream leading to spray nonuniformities. Overall a clearer understanding of spray nonuniformities is emerging.

INTRODUCTION

The Air Force Research Laboratory has focused on fundamental studies of Gas-Centered Swirl Coaxial (GCSC) injector in recent years[1-4]. These injectors are of interest for rocket applications, especially in engines using liquid hydrocarbon fuels and oxidizer-rich preburning cycles. Earlier studies have recommended design criteria for GCSC injectors to ensure good atomization performance and allow some throttling of the engine[2]. Recommendations to achieve these goals focus on the observed scaling of the injectors with gas-to-liquid momentum flux ratio; ratios should be kept above 600 at a minimum and, ideally, prolonged operation should be a ratios above 1000[2]. However, performance is only one aspect of successful injector operation: uniformity, in space and time, of the resulting spray is also important for success. As with most injectors, GCSC injectors can produce nonuniform sprays under certain conditions[3].

As detailed in earlier work[3], spray nonuniformities fall into two main categories—centerline departures and pulsing. Centerline departure behaviors are characterized by the spray centerline and injector centerline not being collinear. The offset of the centerline may vary in magnitude and direction with time or it may be stable. Pulsing appears as a sudden increase in droplet size or number or a change in cone angle. Drawings of the different categories appear as Figs. 1 and 2. Both behaviors are undesirable in a rocket engine. Centerline departures could lead to heat streaks along the chamber wall or poor interelement mixing. Pulsing could lead to changes in flame temperature and/or location. Either could be a catalyst for combustion instabilities. Clearly, then, it is important to avoid, minimize, or, possibly, learn to exploit these behaviors. An improved understanding is needed to build confidence that this can be achieved. Some insight has already been achieved. For example, it is already known that stability can be greatly enhanced by operating at elevated gas-to-liquid momentum flux ratios—at least 600 or higher (see Fig. 3)—and by careful selection of interior injector geometry[3]. However, the ultimate

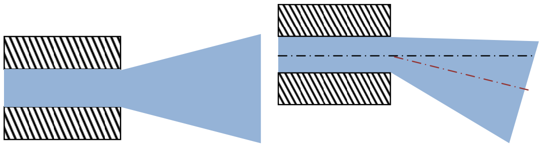


Figure 1: A cartoon of a spray before and during a centerline departure nonuniformity.

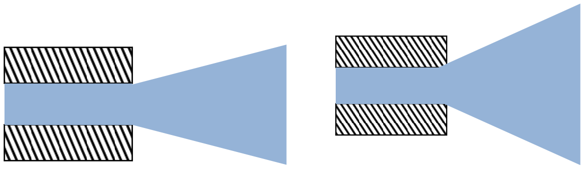


Figure 2: A cartoon of a spray before and during a pulsing nonuniformity which increases the spray angle.

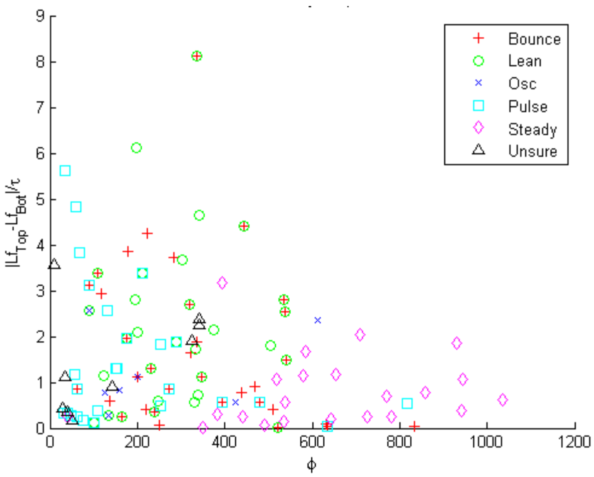


Figure 3: The different spray behaviors, as observed by eye, are given on a graph of normalized film length difference (between the two sides) as a function of momentum flux ratio.

cause of the nonuniformities and the link between intact liquid (film) and spray behavior remains unclear.

The current work focuses on exploring the relationship between film behavior and spray behavior, especially when nonuniformities are observed. Some qualitative links between the two have already been observed[3]. For example, bouncing sprays have a spatially localized area of lower droplet concentration near the injector outlet whose existence is intermittent; the traveling structures resembling waves which have been observed in some pulsing sprays are another example. The presence of intermittent and traveling structures suggests that flow features might possess periodicity. Consequently, video of the intact liquid was analyzed for the presence of dominant frequencies. The existence, size and feature associated with the frequency were compared to observations of spray nonuniformities. Difficulties in comparisons illustrated that naked eye observation did not fully capture the spray behavior. As a result, a few conditions were selected for more elaborate spray analysis which involved acquiring and processing high speed backlit video of the spray. The high speed video clearly demonstrated that even films which seem “steady” when viewed with the eye are not necessarily without nonuniform behavior, as had been suspected earlier[3]. The spray video shows promise in quantifying nonuniformities as well. Finally, correspondence between film- and spray-feature frequencies is observed.

EXPERIMENTAL SET-UP

Much of the experimental hardware and set-up have been detailed in other works[4]; only the minimal amount of information is given here, particularly small set-up changes and additional work related to spray imaging. Most of this section focuses on the image and data processing techniques employed.

All of the work reported here was conducted using nitrogen and water as simulants for gaseous oxygen and liquid hydrocarbon. Flow rates are metered using sonic nozzles and cavitating venturis, respectively. The accuracy of the flow rates is +/-0.25%. The injector used was modular in nature with geometry varying as shown in Table 1. A schematic of the injector, which gives the definitions of the various parameters, is provided as Fig. 4. In GCSC injectors, liquid enters the injector through tangentially drilled holes; a swirling annular film is produced. High speed (nonswirled) gas enters along the film’s axis. For optimal operation, all atomization occurs within the injector (i.e., the length of the film is less than the length of the injector). In the GCSC injectors reported on herein, the liquid film is initially sheltered under a lip to provide better developed liquid conditions at the point of gas-liquid contact.

High speed video was taken, separately, inside the injector cup and downstream of the injector body. A Vision Research Phantom v7.3 camera was used to obtain the video. Lighting for the in-cup (film) video was provided by two variable-power, dpss lasers. The laser beams were formed into sheets using identical sets of optics. The sheets were diametrically opposed and just off of the centerline of the injector body. (A slightly off-axis location, ~1-2mm, improves the amount of light received by the camera and the contrast of the image.) The camera is located perpendicular to the laser sheets. Downstream (spray) video was backlit using a halogen flood light with an acrylic diffuser. All video was taken at 6006 frames per second. The exposure time for the in-cup video was 110 μs; the exposure time for the downstream video was 3 μs, since more light was available in the backlit configuation.

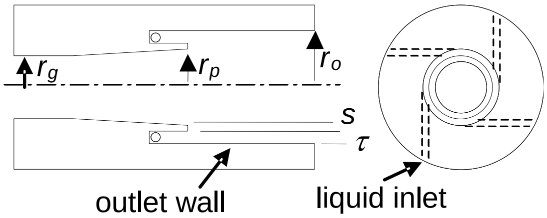


Figure 4: In this schematic of a gas-centered swirl-coaxial injector r_p represents the initial gas post radius, r_g the gas radius at the end of the sheltering lip, r_o the outlet radius, s the step height and τ the gap height. Table 1 lists the values of these dimensions used in the experiments.

Name	r_o (mm)	τ (mm)	r_g (mm)	s (mm)
ODHNTN	7.620	1.651	4.445	1.524
ODPDTN	7.620	1.651	5.461	0.508
ONPDTD	9.525	1.321	5.461	2.743
ONHNTD	9.525	1.321	6.350	1.854
ONPDTN	9.525	1.651	5.461	2.413
ONPNTN	9.525	1.651	6.350	1.524
ONPUTN	9.525	1.651	7.468	0.406
ONPNTU	9.525	1.981	6.350	1.194
OUHUTD	11.43	1.321	7.239	2.870
OUHUTU	11.43	1.981	7.239	2.210

Table 1: Insert names and their attendant geometries are given above. The naming convention is to list the relative size of the (O)utlet and (P)ost radii and the film (T)hickness as either (D)own or (U)p from (N)ominal. In some inserts the (H)eight of the step plus film thickness is referenced instead of the gas post radius.

All video was processed using in-house developed software written for Matlab (version R2008b). The initial goal of the processing was to determine the boundary of either the film (intact liquid in the injector cup) or the spray (atomized liquid downstream of the injector body). The location of the boundary was then used to calculate additional parameters of interest. Different boundary-finding methods were used for the two types of video.

The film boundary is always marked by a sudden transition from bright to dark. A typical in-cup image which illustrates this is given as Fig. 5. Due to changes in film thickness and changes in lighting intensity along the injector axis, resulting from droplet dynamics within the core gas flow, the brightness (aka intensity) of the film and background are not necessarily uniform. These lighting inconsistencies mean that the most straightforward method—thresholding, where a set value of brightness is used to segregate the film from the background—could not be used. The change in brightness from film to background was utilized instead. When moving from the center of the injector into the film the brightness decreases continuously over several pixels. The edge of the film is located within this long run of decreasing intensities; its exact location is indicated by the steepest change from one pixel to the next. In well-lit and behaved images the difference between this location and the boundary determined "by eye" is within 2 pixels; the variation from user to user making "by eye" selections is also 2 pixels. (This accuracy is not affected by the slightly differing scales between videos; two pixels corresponds to just under 0.005 inches in most videos.) In areas with less contrast the variation in both program-to-user and user-to-user edge selection can be larger, so exact determination of accuracy is difficult. Luckily, large departures and seemingly erroneous values are generally limited to single or small runs of pixels. Any results with large or systemic variations between by-eye edge locations and program-found locations are considered too complex for the software to handle and not reported on here.

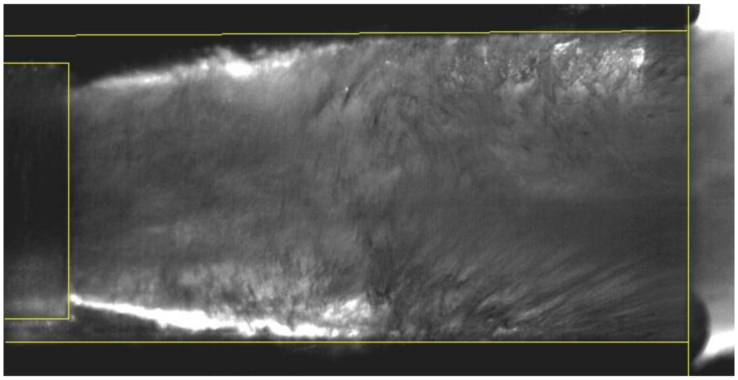
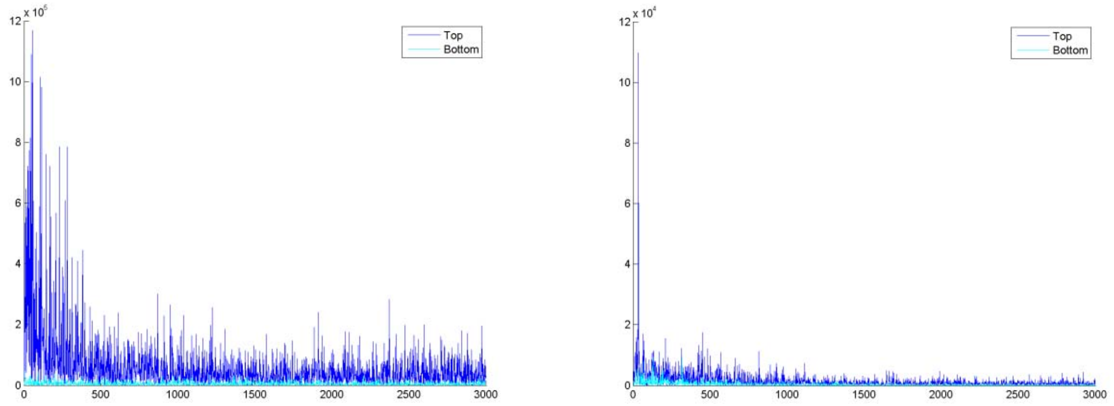


Figure 5: A typical image from the in-cup video is shown here. The edges of the injector body are highlighted including the sheltering lip. This image also shows the intensity transition at the edge of the film and the variation in lighting which can cause trouble in the image processing. Geometry ONPNTU appears here.

Once the film boundary is extracted from the image it is processed to determine film length and film height. The length is set at the first point where the film edge reaches and stays within 1 pixel of the wall location. Because there is some chatter in the film edge at the level of the wall due to rewetting via droplet impingement, an additional constraint is implemented: a span of pixels is considered wherein the film edge must be at or near the wall location (within 1 pixel) for the majority of the span. The location of the wall is determined by eye from videos of short films; all videos taken



(a) (b)

Figure 6: Two spectral density plots of the film length. (a) shows a film without a single dominant frequency while (b) has a dominant frequency. Results are from geometry ONPNTN and ODHNTN, respectively.

on the same day with the same geometry are considered to have the same wall location. Examination of multiple videos of short films indicates this is a good approximation; it is necessary to provide the wall location for all videos because the wall-liquid interface is not visible (only the wall-gas interface is visible). Height is determined at a series of "stations" as the difference between the film location and the wall location. The height is averaged over 7 pixels, 3 on each side of the station. This averaging helps to minimize any errors in edge determination. Stations are closely spaced near the sheltering lip; the first five are 0.051 inches apart. After 0.255 inches (five stations) the remaining stations are located at 0.1 inch intervals.

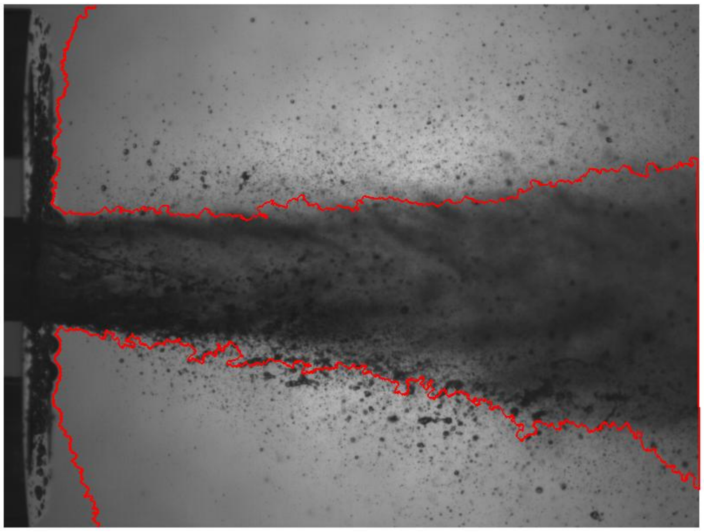


Figure 7: A typical image with the boundary, as found using Otsu's method for a thresholding value, is shown here. Note that due to slight imperfections in lighting intensity, a shadow near the injector face is erroneously captured.

The length of each side of the film and the height of the film at each station and on each side were processed using an fft. Spectral density plots were then examined. 4096 (2^{12}) frames were processed with the fft. Two sample results can be seen in Fig. 6. Figure 6a shows a plot where no single dominant frequency appears to exist; Fig. 6b shows a plot with a strong peak indicating the presence of a dominant frequency. A dominant frequency was said to exist if a single peak, or series of resonant peaks, were more than 50% higher in power than other peaks. The comparative size of the height disturbances versus the overall film height and noise (film heights are typically under 30 pixels with disturbances generally less than 50% of the overall height) likely result in some loss of fidelity so that this technique may not capture all frequencies present in the film.

The spray data was processed using a simple thresholding technique. Otsu's method[5] was employed as a way to determine the thresholding value separating foreground and background pixels (the spray versus the background lighting). A trace was made of the edge in the resulting black and white image. A typical result is shown in Fig. 7. Note that some initial error in the boundary is incurred due to slight inconsistencies in backlighting and a shadow of the injector face. From this trace the spray width and centerline could be determined. The preliminary results reported here were calculated from only

1500 frames. The spray width, centerline location and absolute location of the boundary at selected points downstream of the injector (as a function of time) were processed using fft's to determine if any periodic evolution existed in the sprays.

RESULTS AND DISCUSSION

Initial comparisons between the film and spray were made using information determined solely from observing the spray with the naked eye. Unaided examination of the spray produced several limitations. First, there was no way to determine if the various unsteady behaviors such as centerline bouncing, "popping" sounds and pulsing in the spray were truly periodic or just intermittent. This limitation was further troublesome due to limited resolution in the film frequencies. Observed changes in the spray generally occurred on time scales of seconds or longer. If these behaviors are linked to periodic changes in the film, then the frequencies would be less than one Hertz—below the current resolution. Also, the eyes are limited in the range of frequencies they can detect, so a spray may appear steady but actually move at a rate which is undetectable. Earlier observations had indicated that this was indeed the case[3]. Additionally, it can be difficult to determine when multiple behaviors are occurring simultaneously—for example, a spray may pulse and bounce but the pulsing may mask small changes in the centerline. The swirling of the underlying liquid flow adds to this difficulty.

Just over 100 cases—encompassing a wide range of operating conditions and geometry—were examined. About 75% of the films exhibited a single dominant frequency in either the length or the height (at least one station). With the experimental and processing set-up, frequencies up to 3003 Hz could be recovered with a resolution of 1.36 Hz. Detected frequencies ranged from the lower limit observable to 350 Hz. The vast majority of frequencies were in the range of 8-100 Hz, with less than 1% over 100 Hz. There were no dominant frequencies detected above 350 Hz and, in general, the spectral power at those higher frequencies was low compared to the spectral power of frequencies below this value. These 100 cases exhibited the complete assortment of nonuniform behaviors including numerous "steady" sprays, and the full range of nonuniformities was encompassed within the percentage of films with single dominant frequencies. Periodicity was even observed in several films where the accompanying spray was described as steady—not surprising given the limitations of naked-eye observations. No correlation was found between the existence of a single dominant frequency in the film, or its value, and the existence or types of nonuniformities.

Earlier observations of the in-cup behavior had shown some nonuniformities—such as bouncing and asymmetric pulsing—were accompanied by localized disturbances[3]. This localization of disturbance could mean any resulting periodic behavior would be localized to one area of the film. For example, since asymmetric pulsing is often accompanied by waves which are visible on only one side of the film then it seems reasonable that the accompanying film might exhibit periodicity on only one side. On the other hand, axisymmetric pulsing is often accompanied by waves on both sides of the film which could result in films with dominant frequencies on both sides. There is a reasonable expectation, then, that some correspondence exists between locations where films exhibit dominant frequencies and the nonuniformities observed in the spray. Indeed, in many instances only the height or only the length exhibits a dominant frequency. Additionally, it is common that only one part (either a few station locations and/or one side) of the film exhibits a dominant frequency. (There are several tests, however, where frequencies are observed on both sides of the film and/or in the height and the length. In the vast majority of these tests the dominant frequency is the same, within the accuracy of the method, across all locations.) Unfortunately, an association between location of the dominant frequency and the type of nonuniformity was not observed. Perhaps this lack is due to the above-cited limitations in by-eye spray observations. The existence and detection of an association is also complicated by the swirling nature of the spray. Axisymmetric pulsing may not be truly axisymmetric but may, instead, be asymmetric and precessing so that it appears axisymmetric to the unaided eye; similarly, bouncing is rarely limited to one plane. Furthermore, localized behavior may exist only in a part of the film which is not illuminated or there may be enough movement in and out of the thin, illuminated plane to mask periodic behavior.

The lack of findings in film-to-spray comparisons and the limitations noted in unaided observations of the spray led to the decision to take high speed video of the spray. A limited number of sprays were, therefore, targeted for further study. Only tests where the film exhibited very dominant

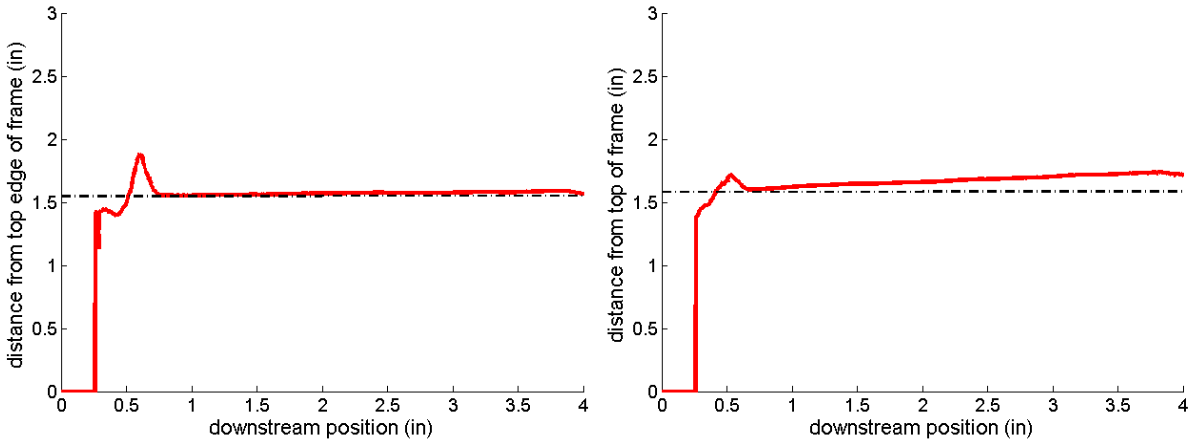
Test #	Film	Spray	Behavior
ODHNTN-1	17	17	Bounce
ODPDTN-1	31	27	Steady
ONHNTD-1	35	25	Steady
ONPDTD-1	30	30	Pulse
ONPDTD-2	9	8	Bounce
ONPDTN-1	29	32	Oscillate
ONPDTN-2	6	5	Bounce
ONPDTN-3	29	27	Oscillate
ONPNTN-1	24	20	Unknown
ONPNTN-2	30	25	Steady
ONPNTU-1	45	x	Unknown
ONPNTU-2	61	x	Pulse & Lean
ONPUTN-1	97	?	Pulse
OUHUTU-1	41	50	Bounce

Table 2: The dominant frequencies, in Hz, found in the film and in the spray are given along with the spray behavior as observed by eye.

frequencies were selected. By very dominant it is meant that the film exhibited the same frequency across multiple height stations. (Generally, if the film existed at a given station then the height exhibited a frequency in these selected tests.) Also, the frequency appeared in both sides and/or in both the height and the length. Enough tests were retained to span the full range of nonuniform behaviors as noted from by-eye observation, including steady sprays. A span of frequency values from 6 to 100 Hz were also represented in the selection. The operating conditions, injector geometry and measured frequencies are given as Table 2.

As expected, the spray video showed much richer behavior than that observed during real-time viewing. Many sprays seemed to exhibit multiple types of nonuniformities simultaneously—occasional pulsing was seen in nearly all sprays, including those which had prevalent bouncing. Additionally, it was observed that sprays labeled "steady" when did have nonuniformities. It seems likely that sprays labeled as steady when observed by eye but exhibiting dominant frequencies in the film are most likely not steady. Pulsing behavior was never observed to occur axisymmetrically; instead, pulses were localized to one area of the film, but might be quickly followed by pulsing in another area. It remains likely, but unclear, that axisymmetric pulsing is merely a limitation of the human eye and all pulsing is asymmetric with what was previously termed axisymmetric pulsing being the result of several asymmetric pulsing events.

From the outline of the spray, the spray centerline can be calculated as a function of downstream distance. Small deviations in the centerline are more easily observed from these graphs than from the raw video. Also, quantitative results are available with this technique that can indicate the degree of departure from the injector centerline and the percentage of time the spray is not centered (or nearly centered) with the injector. A fft of the calculated location can show if the centerline varies periodically; these results are discussed in more detail below. Time-averaged plots of the centerline as a function of downstream distance show that some tests, even though they exhibit centerline departures at discrete times, have no average departure in centerline. Others have a definite overall offset, however. Figure 8 shows two time-averaged centerline profiles for sprays exhibiting centerline departure nonuniformities—one is centered on average and the other is biased on average. It is important to know that time-



(a)

(b)

Figure 8: The time-averaged centerline position does not always show a deviation from the injector centerline even if there are instantaneous departures of the two centerlines. Spray ODHNTN-1 (a) has no departure, on average, but spray ONPDTD-2 (b) does.

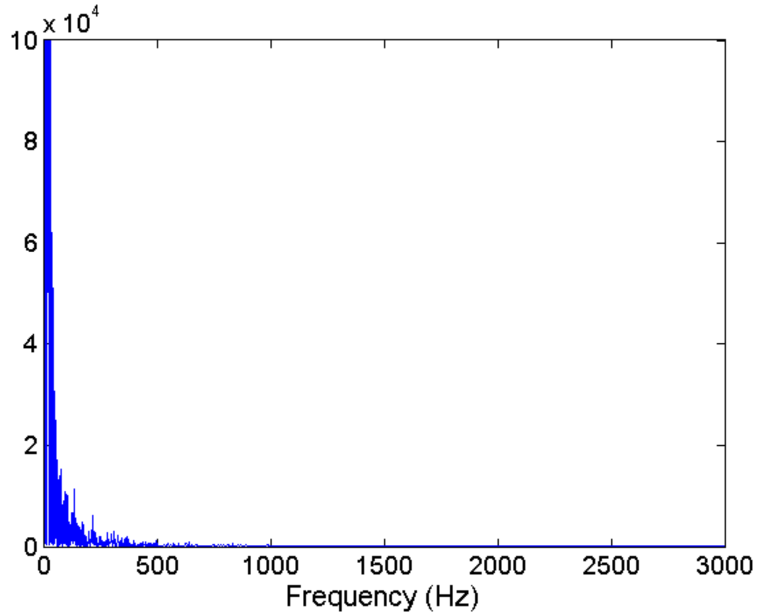


Figure 9: No single dominant frequencies were seen in the spectral density plots of the spray—a typical one of which is shown here.

averaged results can mask nonuniformities because several techniques to study sprays return only time-averaged results (e.g., patternation[6]). At the same time, the time-averaged plot does not tell the full story of the nonuniformities since, in these calculations, centerline departures could arise from either leaning/bouncing behavior or from repeated asymmetric pulsing localized to one side of the spray..

In addition to the centerline, the spray width was calculated from the boundaries. This quantity could give an indication of pulsing behavior. However, because axisymmetric pulsing was not observed, the width information must be combined with the boundary information to get a clear picture of the spray's behavior. The width was useful on its own to develop an idea of whether pulsing nonuniformities were periodic. (Again, as with the centerline, the frequencies are determined by processing the width, at discrete locations, with a fft.)

Power spectrum data were derived for the cross-stream location of both "sides" of the spray boundary at various downstream points in addition to the centerline and the width of the spray. The graphs of spectral density versus frequency, Fig. 9 for example, indicate a large frequency spectrum in the spray. Because only 1500 frames were processed, however, there are not clear frequency peaks: the bins in the fft are rather large and, as a result, the frequency, or, in most cases, several frequencies, present is not an integer multiple of the bin size. The vast majority of the frequency graphs have the same basic character shown in Fig. 9. While these graphs are insufficient to determine dominant frequencies in the range found within the films, there are some interesting findings. There is a lot of content in the low frequencies, as might be expected from the film results and binning issues, but almost no content above ~400 Hz. In many tests there is essentially no content above 200 Hz. So, the spray does not appear to exhibit high frequency behavior (within the limitation of 3003 Hz imposed by the video framing rate).

Because no single dominant frequencies could be captured from the limited analysis, graphs of parameters as a function of time were used to determine frequencies. Again, the spray width, centerline and cross-stream boundary location were considered. In many cases a dominant frequency, within the range found in the film, was obvious (Fig. 10, boundary or centerline). In other graphs there was not an obvious frequency (Fig. 10, width). In numerous cases, it was clear that multiple frequencies were present because the traces were periodic but not sinusoidal (Fig. 11). When the latter occurred, the dominant frequency reported is that based on the overall periodicity of the shaped (triangle, square, etc) wave. Because a limited number of frames were processed and the temporal plots were analyzed by hand, there are some limitations on accuracy and range which are difficult to quantify. Repeated measurements show accuracy in the frequency value can only be determined within ~+/-5 Hz. Frequencies above 75 Hz and below 10 Hz were difficult to measure by hand; the former being masked by peaks due to noise and the latter because a full cycle was not visible in the graphs.

Sometimes frequencies were observed in all four examined parameters (width, centerline and both sides of the spray), but in other cases frequencies were not observed in one or more parameters. For example, ODHNTN-1 has a dominant frequency in the centerline and boundary data but not in the width (see Fig. 10). This spray is one which bounces quite a bit but exhibits minimal pulsing; this

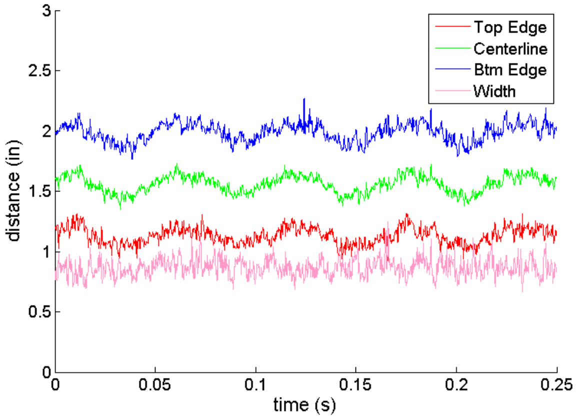


Figure 10: A graph of the various spray parameters analyzed as a function of time gives information about the type of nonuniformity in the spray as well as the dominant frequency. The two boundary locations, centerline and width from test ONHNTN-1 are shown.

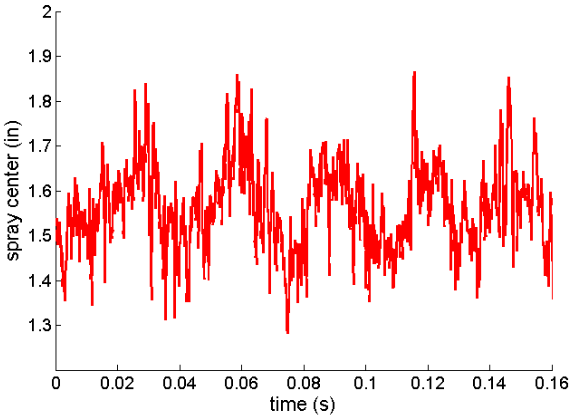


Figure 11: Some of the wave forms departed from a sinusoidal shape indicating that multiple frequencies were present. This graph, for example, shows the movement of the centerline of test ONPDTD-1 1.78 inches downstream of the injector face.

frequency behavior, i.e. no width frequency, was also seen in other sprays which did exhibit pulsing but the pulsing did not appear to have a periodic component. Asymmetric pulsing often occurs at various locations around the spray, so it may be periodic but not captured as such within these backlit images. One spray, ONPDTN-1, exhibited frequencies in all parameters except one side of the spray. Video shows that this spray has asymmetric pulsing alternately on either side, but the spray also exhibits an obvious bounce which only occurs opposite pulsing on the top of the spray; in other words, the spray has a predominant bounce but only one side, the bottom, of the spray moves during the centerline departure. There is, then, some ability to determine nonuniform behavior from just frequency data. This assertion is further supported by examining the phase of the two sides of the spray boundary. In a pure bouncing mode the movement of the two boundaries is in phase, whereas, with pure pulsing the two boundaries are directly out of phase. Phase information is difficult to determine accurately from examination of these time plots, but the selected tests did exhibit a range of phase lag. In all instances where multiple parameters exhibited a dominant frequency, the same value was measured (within the measurement accuracy) for each parameter. There was no obvious correspondence within this limited sample between the location(s) of a dominant frequency in the film and the location(s) of dominant frequency in the spray. This finding is perhaps not surprising given the dual complications of the swirling film and the multiple nonuniformities found within a single spray.

From Table 2, it is clear that there is some correspondence between the value of the frequencies found in the film and those observed in the spray. As expected, disturbances from the film do propagate downstream and appear to be responsible for some of the spray nonuniformity. All types of nonuniformities observed by eye are represented in this finding although spray video generally refutes these simple characterizations. It is interesting to note, however, that not all of the sprays examined exhibited obvious frequencies despite very dominant frequencies in the film. In at least one case, ONPNTN-2, this may be due to limitations in the frequency determining method. In the other tests the lack of correspondence may be a complication of the swirl or it may indicate that not all film disturbances propagate downstream to cause spray nonuniformity. More tests and more advanced frequency techniques are needed to draw a definitive conclusion as to this point. In general, the current results show that much information can be extracted from spray video and that there is some correspondence between film and spray behavior, but additional testing and data processing are still needed to develop a robust understanding of spray nonuniformities.

SUMMARY AND CONCLUSIONS

The film and spray behavior of gas-centered swirl-coaxial (GCSC) injectors has been examined with an eye towards understanding the spray nonuniformities observed in earlier testing. Observations with the naked eye miss much of the rich behavior which sprays exhibit. Limitations of this type of observation make comparisons between spray and film behavior difficult. Analysis of video of the intact liquid film showed more than 75% of tests exhibited dominant frequencies in either the length or local film height. However, attempts to correlate these frequencies with observed spray behavior (using naked-eye observation) failed. This failure may result, in some aspect, from the lack of axisymmetry and swirl exhibited by the film since only a small slice of the film is being recorded and analyzed. Other observations, however, also suggested that the result may be a consequence of the limitations of by-eye spray examination. As a result, a selection of tests was repeated so that spray video could be collected.

In general, the spray video showed a richness of behavior not evident with the naked-eye—nearly all sprays had some amount of both bouncing and pulsing. No truly axisymmetric pulsing was observed; while the sample size was limited, it is believed that observations of axisymmetry were a result of limitations in the human eye and multiple, closely spaced events were interpreted as one simultaneous event. The spray video also allowed some quantitative measure of the degree of nonuniformity, particularly in terms of the amount of centerline offset present at any time or on average. This data also showed that films which have centerline departures at a given instant may have no centerline offset on average; time-averaged measurements would erroneously suggest that the spray did not exhibit a leaning/bouncing nonuniformity.

To date only a limited number of frames of the spray video have been analyzed. These frames are of insufficient number to generate good results from fft analysis, but are sufficient to allow some information about spray periodicity to be determined. Frequencies were extracted from graphs of centerline location, width and cross-stream boundary locations versus time. The extracted frequencies agreed with the frequencies found in the film; although some sprays did not appear to possess a dominant frequency even when the film did. The reason for this uncoupled behavior is not yet clear. Which parameters exhibited dominant frequencies gave good indications about the nature of the nonuniformity. For example, a spray with little pulsing did not have a dominant frequency in its width, but did have a strong frequency in its centerline. Overall, it was determined that many details of nonuniformity can be extracted from the centerline, width and spray location as a function of time, and that there is correspondence between in-film and spray behavior and frequencies.

FUTURE WORK

The richness of behavior observed in the spray video provides much greater insight into nonuniformites and, therefore, spray video needs to be obtained for a wider array of conditions. Additionally, this rich behavior suggests that the film and spray are likely to exhibit unsteadiness that may not be periodic or whose periodicity may be masked by competing behaviors. The general unsteady behavior, e.g. investigation into the existence of “bursts” of unsteadiness, and overall spectrum of frequencies should also be considered. A path to this investigation will be to link two cameras and record in-cup and downstream videos simultaneously. Finally, this video will need to be analyzed for the maximum number of frames available, at least 6006, to obtain resolution down to the 1 Hz level or below—the level at which by-eye observations show nonuniform behavior.

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