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Spray Nonuniformities in Gas-Centered Swirl-Coaxial Injectors (Preprint)

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Abstract

Experimental studies of gas-centered swirl-coaxial (GCSC) injectors have revealed five basic types of nonuniformities in the spray. These nonuniformities can be classified as either affecting the centerline of the spray, with respect to the centerline of the injector, or affecting the temporal mass-distribution. The details of these behaviors are discussed as are possible driving factors and design criteria for avoidance. In general, high momentum flux operations are suggested for minimizing centerline deviations and careful selection of the thickness of the lip initially separating the gas and liquid phases is suggested for minimizing mass-distribution issues.

Introduction

While a known and well-behaved size distribution of droplets is important to the successful operation of most atomizing devices, it is often only a small part of the requirements placed on atomizers. Many uses require atomizers to produce droplets which are uniformly distributed in space and time [1]. As with producing the desired size distribution, producing uniform droplet distributions can be a challenge.

Earlier work demonstrated that atomization performance of gas-centered swirl coaxial (GCSC) injectors can be predicted from the injector geometry and operating conditions [2,3]. The most powerful parameter for predicting performance is the momentum flux ratio of the gas to liquid [2,3]. During the process of validating the performance-predicting model, nonuniformities in the spray were sometimes observed. These nonuniformities were documented and studied because they occur at some of the reasonable operating conditions for the intended application—rocket engines. Here the five types of observed nonuniformities—leaning, bouncing, oscillation and two types of pulsing—are described along with some information on suspected causes. These behaviors are influenced by the operating conditions as well as the injector geometry. The designer would like to eliminate or minimize nonuniformities in most applications, so some suggestions on achieving that goal are also given. In general, two main design principles are given—GCSC injectors should be designed to operate at high momentum flux ratios and they should have geometries with moderate initial distances between the gas and liquid.

Materials and Methods

Many details of the experimental setup can be found in the authors' earlier work [2,3]. The details given here are minimal and relate mostly to background information and changes. A gas-centered swirl-coaxial injector relies on the energetic, fast-moving gas flow to produce droplets from the swirling, wall-bound film. The film is created by introducing the liquid, in this case water, through holes drilled tangential to the injector cup. The unswirled gas, here gaseous nitrogen, enters down the centerline. A schematic of the current injector is given in Fig. 1. This injector was designed to be modular with the variation of geometric parameters given in Table 1. Upstream of the modular acrylic section is a stainless steel section which consists of ~180 mm of gas inlet with a fixed radius of 6.35 mm (0.25 inches). While the experiment was designed to take advantage of differing gas velocities produced by changing the gas-post radius just prior to liquid contact, the change in geometry also produces a variation in the height of the lip initially separating the gas and liquid flows.

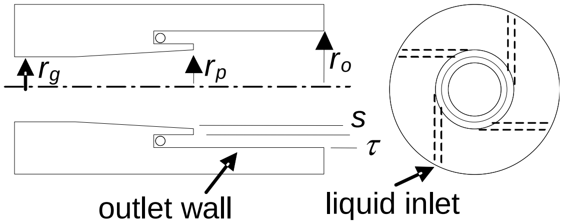

Figure 1: A schematic with the relevant modular dimensions listed. Table 1 lists the dimensions as used in the experiments; r_p is fixed at 6.35 mm

All tests are performed with atmospheric back pressure. The gas flow rates were varied from 0.0187-0.0798 kg/s. The liquid flow rates were varied from 0.0236-0.0794 kg/s. The momentum flux ratio, defined using the mass flow rates along with flow areas based on the initial film thickness for the liquid and the average gas post height—$(r_p+r_o)/2 = r_p+(s+\tau)/2$, varied from around 10 to around 1100 [3].

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A dpss laser beam was split and expanded into two sheets. These sheets were oriented 180° from one another along the centerline of the injector or spray. Using this lighting, high speed images were taken with a Vision Research Phantom v7.3 camera positioned 90° from the laser sheets. Either the acrylic outlet section of the injector was visualized (from the liquid inlet to the injector outlet) or, for select tests, the spray was recorded from the injector exit to about 63 mm downstream. The video of the spray was captured at 3000 fps with an exposure time of 310 microseconds while the in-cup video was captured at both this rate and at 6006 fps with an exposure time of 150 microseconds. The laser provided insufficient lighting to achieve the 6006 fps rate in the spray.

Name	r_o (mm)	τ (mm)	r_g (mm)	s (mm)
ODHUTD	7.620	1.321	3.429	2.870
ODPDTD	7.620	1.321	5.461	0.838
ODHNTN	7.620	1.651	4.445	1.524
ODPDTN	7.620	1.651	5.461	0.508
ODHUTU	7.620	1.981	3.429	2.210
ODHDTU	7.620	1.981	5.461	0.178
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
OUHDTD	11.43	1.321	9.271	0.838
OUPNTN	11.43	1.651	6.350	3.429
OUPUTN	11.43	1.651	8.407	1.372
OUHUTU	11.43	1.981	7.239	2.210
OUPUTU	11.43	1.981	8.407	1.041
OUHDTU	11.43	1.981	9.271	0.178

Table 1: The 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.

Results and Discussion

Two main categories of nonuniformities were observed—spray centerline departures (from the centerline of the injector) and pulsing. Three types of centerline departures occurred which can be characterized by the stability of the spray's centerline and the degree of departure—leaning, bouncing and oscillating. Leaning occurs when the centerline of the spray is obviously, usually several degrees, not aligned with the centerline of the injector and the spray maintains that position either indefinitely or for 10's of seconds. When the centerline is obviously misaligned but the spray's center changes over seconds or tenths of seconds then the spray is bouncing. Oscillating sprays exhibit very rapid changes in the spray's centerline location (generally less than 0.1 seconds). The centerline deviation is smaller during oscillating than leaning or bouncing. Pulsing can be divided into axisymmetric and asymmetric pulsing. Axisymmetric pulsing is characterized by an axisymmetric, or nearly so, disturbance on the film surface which, when it exits the injector, results in a distributed pulse of larger droplets, increased droplet density or a sudden increase in spray angle (or some combination thereof) . Axisymmetric pulsing is often accompanied by an audible popping noise. If the disturbance is not fully tangentially distributed then asymmetric pulsing occurs. Localized jets of larger droplets or higher droplet density appear with asymmetric pulsing. Figures 2-4 show sprays exhibiting centerline departure behaviors while Figs. 5 and 6 show sprays displaying pulsing behavior.

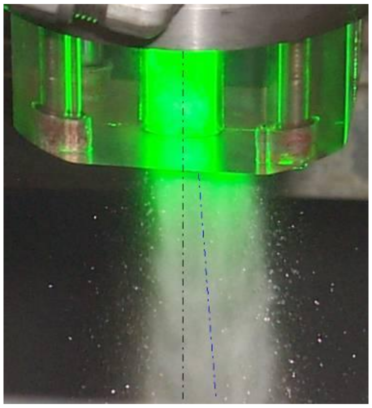

Figure 2: Leaning exists when the spray centerline differs from the injector centerline. This photograph is annotated with the centerline of the injector (black) and the spray (blue).

A range of mass flow rates and geometries were tested. For each geometry shown in Table 1 a sweep of momentum flux ratios over three orders of magnitude—O(10) to O(1000)—was tested. Observations of nonuniform behavior suggest that the higher the momentum flux ratio, the more stable the spray will be. This uniformity is reflected somewhat in the stability of the film length—high momentum flux operating conditions tend to produce sprays with lower standard deviation in film length [2]. Several inserts, particularly those with 7.620 mm outlet radius, exhibited nonuniformities only at the lower momentum flux ratios tested. Additionally, higher momentum flux ratio operations are most likely to exhibit oscillations rather than other types of nonuniformities. Due to its rapidity and low deviation from centerline, this nonuniformity is likely to be the best tolerated in most applications. Indeed, if the oscillation frequency is well away from any chamber frequencies or resonances then rocket engines can likely probably tolerate this behavior. In terms of geometries, small steps (knife edges) are particularly

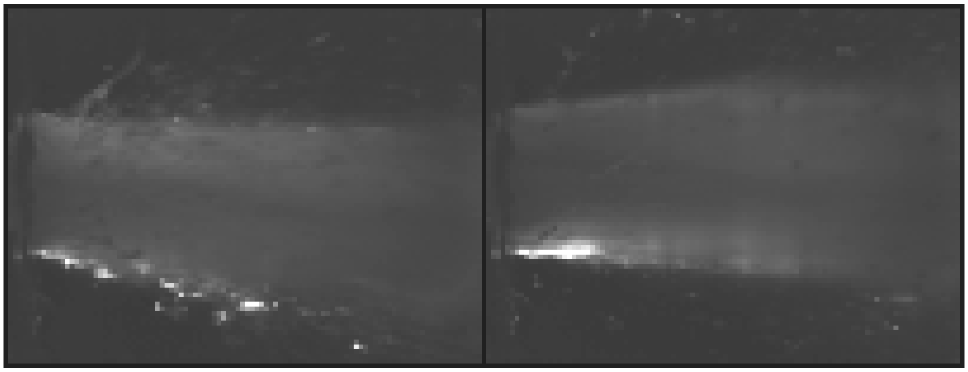

Figure 3: Two frames of video (~81.5 ms apart) show the two typical states for a bouncing spray.

Figure 4: Three frames of video (~1.33 ms apart) show the typical path of an oscillating spray.

Figure 5: An image from a film undergoing axisymmetric pulsing. Waves are denoted with arrows.

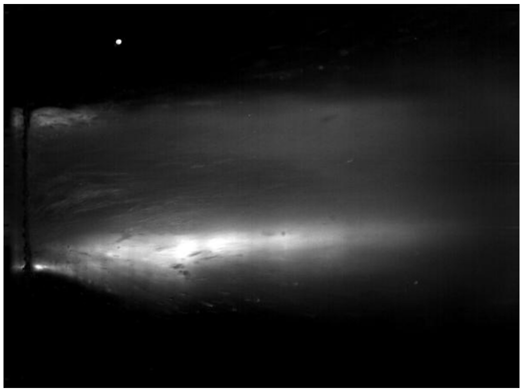

Figure 6: Asymmetric pulsing is shown in the film. The arrows denote waves on the surface of the film.

unstable and prone to pulsing behavior. Large steps also seem to create problems due to strong gas-phase separation (and its interaction with the liquid) and the potential to choke the flow prior to liquid-gas contact. The largest lips tested here were prone to bouncing and pulsing when the outlet diameter was large, but exhibited very uniform behavior when the outlet diameter was small. In general, smaller outlet diameters were more uniform than the larger outlets, so the size of the gas core appears to effect stability. With these general observations and guidelines in mind, each nonuniform behavior is examined in more detail below.

Leaning was initially believed to result from machining errors or inlet-line biasing. However, clocking the injector and reorienting the inlet line (a flex line) did not alter the leaning behavior with respect to the laboratory coordinates. Additionally, regardless of how the flow conditions are approached, a given geometry and operating condition always produces the same leaning behavior. Further investigation revealed an anomaly at the trailing edge of the injector cup as shown in Fig. 7a. A zone exists near the injector outlet which is devoid (or mostly so) of droplets. This zone causes the displacement of the gas flow leading to the leaning behavior. Since the only droplet-free gas is that outside of the injector and spray cone, it appears that this gas is being pulled into the injector, possibly due to some flow separation at the exit. This finding is further reinforced by the fact that the spray is not fully

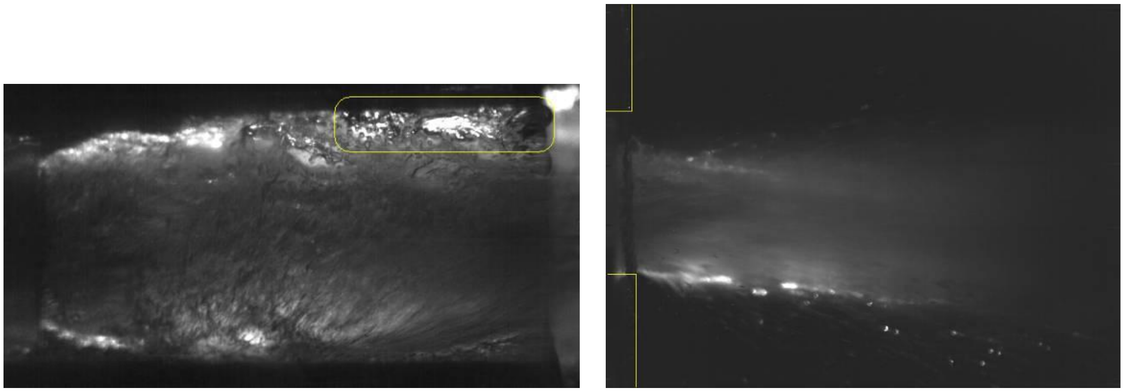
(a) (b)

Figure 7: Leaning sprays show a droplet-free zone (a) and are not attached to the injector wall at the exit of the injector (b). In (b) the injector edges are highlighted with yellow lines.

attached to the edge of the injector outlet (Fig. 7b). The exact cause of this behavior is not yet known, however. Experiments, discussed at the end of this section, show that leaning is related to momentum flux ratios, not just gas or liquid flow rates. It is also likely to be strongly influenced by injector length but this factor has not yet been thoroughly examined.

Bouncing appears to be, essentially, a movement between centered and leaning states or, occasionally, a movement between two leaning states prior to a change in leaning direction or the onset of oscillating behavior. As with leaning, a downstream zone of droplet-free gas appears. However, when bouncing occurs this zone grows then shrinks or is shed downstream. When the zone collapses, shrinks or is shed then the gas flow rebounds and the core, droplet-laden gas flow briefly takes on a sinuous shape within the injector body. No changes in the liquid film behavior are observed prior to the initiation or termination of the droplet-free zone, although increases in film length often occur following the removal of this zone. Furthermore, the perturbed core flow generally restabilizes prior to the formation of another droplet-free zone. These findings suggest that the rebound from one incident is unlikely to be the initiator of a subsequent cycle. As the main driver for leaning is not yet understood, the exact mechanisms for bouncing also remain unknown; yet, it is clear that the two behaviors are strongly related.

Rapid movements about the centerline, oscillations, can be somewhat difficult to observe, especially with the naked eye. The spray may appear to have an increased cone angle instead of a moving spray centerline. Indeed, high-speed images of sprays thought to be stable suggest that very few sprays are truly stable, but instead exhibit some small degree of oscillation in the absence of other nonuniformities. The droplet-free zone near the injector outlet was not observed during oscillation, but this could be due to the rapidity of the behavior and the zone's likely smaller size (smaller departures are accompanied by smaller zones). Unlike bouncing and leaning, oscillating is clearly accompanied by changes in the liquid film: at high momentum flux ratios oscillation is accompanied by rapid changes in film length where the film will briefly and repeatedly become substantially longer. Occasionally, oscillation occurs at relatively low momentum flux ratios; these longer films exhibit many fast-moving waves, as in asymmetric pulsing but more frequent than commonly observed with pulsing. Considering these two obvious film behavior changes oscillation, despite generally occurring at the high end of bouncing, seems to have different driving forces than the other centerline-departure behaviors. Given the similarities with some of the pulsing behaviors, oscillation may be primarily driven by unsteady flow over the internal separating lip of the injector.

Pulsing can also be difficult to observe with the naked eye since a pulse of liquid travels through the spray at speeds approaching that of the gas flow—often 100's of feet per second. The more regular the pulsing is, the easier it is to observe. Another aid is an audible pop, likely due to the liquid's constriction of the gas flow, which occasionally accompanies axisymmetric pulsing; popping was never heard in the absence of pulsing. As noted above, there are two types of pulsing. Both types are accompanied by an axially localized increase in film thickness—a "wave". Asymmetric pulsing occurs when this wave is also tangentially localized while axisymmetric pulsing is related to a tangentially distributed wave. (Note, however, that small departures from axisymmetry still occur, likely as a result of the swirling liquid velocity.) Examples of the film profiles during each type of pulsing are given as Fig. 8. These waves are believed to result from the interaction of the liquid and gas at the end of the separating lip. Earlier CFD studies showed disturbances may result from two different mechanisms [4]. The separating lip causes a recirculation zone and liquid can be pulled up along the step then forced downstream or the interaction of the gas and liquid

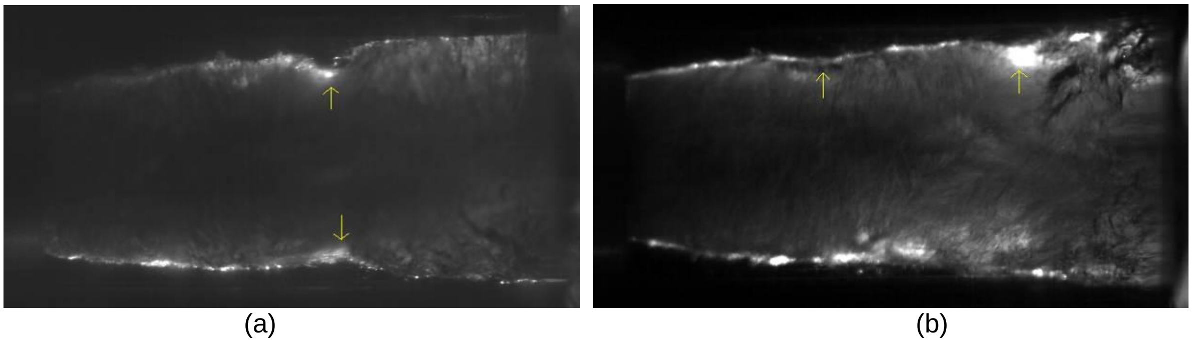

Figure 8: In-cup video frames show axisymmetric (a) and asymmetric (b) pulsing. Arrows show the approximate center of the waves to aid in their visibility. Different injector geometries are shown.

can cause the recirculation zones, along with a mass of liquid, to be shed downstream. The latter is shown in Fig. 9. Experience and these results suggest that both extremes of lips should be avoided. Very thin lips, "knife edges", produce a lot of vorticity through the sudden contact of high speed liquid and low speed gas which is likely to produce more disturbances [5]; also, knife-edges with shallow angles allow a lot of liquid to be easily pulled up along their surfaces. On the other hand, very thick lips can produce stronger separated flow and allow more liquid to fill in behind the step. This liquid is more distant from the main liquid flow, so it may be more easily displaced in large amounts.

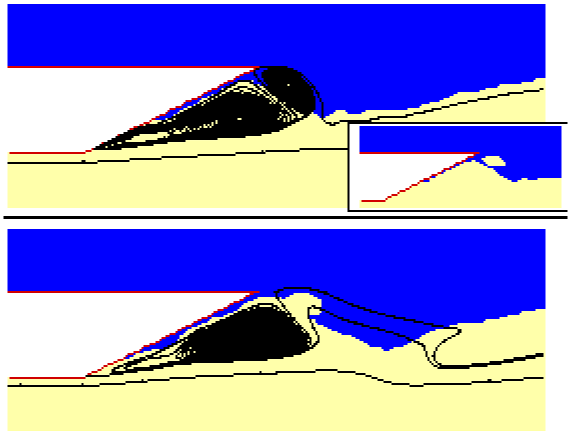

Figure 9: A close-up view of the lip (white) separating the liquid (blue) and gas (yellow) as well as some streamlines (black) is given. Liquid is pulled up the step but a wave of fluid is produced when the gas-liquid interaction cause the secondary recirculation zone to decay. Then both the primary recirculation zone and a mass of liquid move downstream.

The film height was extracted at 14 locations along the injector and an fft was performed on the data to determine if these wave structures spawn and move at distinct frequencies. An fft of the length was also taken to determine if pulsing films have periodic length variations. The data indicate that a small range of frequencies, generally 10-20 Hz in width, is detectable in both the film height and many of the film lengths; in some films a second band of higher frequencies (at much lower strengths) is also detected. These large wave-like structures seem to move downstream with dominate frequencies under 100 Hz. Secondary frequencies can be up to nearly 800 Hz. Because a limited range of operating conditions produce pulsing in each geometry, and some geometries produce no pulsing, there are insufficient data to develop clear relationships between frequency and geometry. However, the data clearly indicate that momentum flux ratio alone is insufficient to collapse the frequency data. This finding is unsurprising given the idea that recirculation, which is greatly affected by step geometry alone, drives the pulsing behavior.

To further examine operating envelopes and their effect on nonuniformities, geometry ONPNTN was operated at a fixed liquid flow rate (0.0336 kg/s) while the gas flow rate was slowly increased from 0.0122 to 0.0717 kg/s. As the gas velocity increased the spray changed from a two-cone, stable, centered spray to a bouncing then leaning spray. Further increases in gas velocity again produced bouncing then leaning in the opposite direction. At the highest range of gas velocities oscillation was observed. A table indicating the exact behaviors at given operating conditions is given in Table 2. Following this experiment, a similar operation was performed with a fixed gas flow rate (0.0363 kg/s) and increasing liquid flow rate (0.0268 kg/s to 0.0513 kg/s). A similar shift in behavior was observed despite the opposite fluid being varied and the opposite trend in momentum flux ratio (now decreasing instead of increasing). Again, these results suggest higher momentum flux ratios produce oscillation and at least generate sprays with no directional bias. However, the geometry will often limit the momentum flux ratios available to meet the mission needs, so careful prior selection of geometry remains necessary.

Gas mass flow (kg/s)	Liquid mass flow (kg/s)	Approximate Momentum flux ratio	Behavior
0.0122	0.0336	24	Start point; little center spray but seems uniform
0.0272	0.0336	117	starts bouncing to left, eventually leans left
0.0322	0.0336	164	starts to bounce right, eventually leans right
0.0445	0.0336	313	bounces fully left-to-right
0.0499	0.0336	395	oscillates
0.0717	0.0336	814	Stopping point, still experiencing oscillations
0.0363	0.0268	328	Start point; oscillating
0.0363	0.0272	317	begins bouncing right, eventually leans right
0.0363	0.0363	179	starts bouncing left, eventually leans left
0.0363	0.0467	108	bounces to left but mostly centered
0.0363	0.0513	90	Stopping point

Table 2: The gas mass flow rate was varied with the liquid flow rate was held constant, and vice versa. Due to the manner of experiment, the accuracy of these flow rates is less than the main experiment—perhaps 0.005 kg/s.

Conclusions

Testing of a gas-centered swirl-coaxial injector found evidence of five types of spray nonuniformites. These nonuniformities may be grouped as effecting the spray centerline—leaning, bouncing and oscillating—or effecting the temporal distribution of mass—axisymmetric and asymmetric pulsing. Both groups of nonuniformities are due to interactions between the gas and the liquid; several obvious root causes such as machining errors and inlet biases have been ruled out. The behaviors are repeatable for a given geometry and operating condition. Reproducible centerline disruptions are found at similar momentum flux ratios (and a fixed geometry) both by holding the gas flow constant while varying the liquid flow rate and by holding the liquid constant while varying the gas flow rate. The root causes of the nonuniformities remain under investigation; however, bouncing and leaning appear to be related to the formation of a droplet-free zone at the end of the injector cup. Leaning occurs when this zone is stable, and bouncing occurs when it is not. Oscillating may also be related to this gas-phase anomaly, but there is no visual evidence of a droplet-free zone. It seems oscillation may, instead, be due to the unsteady flow of gas and liquid at the separating lip, just like pulsing. Pulsing is caused by the formation and shedding “bumps” of liquid as observed in in-cup visualizations. The initiation mechanism of the bump is believed to be related to the unsteady flow near the separating lip.

The lip geometry, gas-post and outlet radius and operating momentum flux ratio are important parameters for developing injectors with minimal or no nonuniformities. The higher the momentum flux ratio (a range of ~10-1100 was tested) the more uniform the spray tends to be. Some injector geometries exhibit nonuniformities at low momentum flux ratios but become uniform as the ratio is increased. Nonuniformities at high momentum flux ratios tended to be oscillations rather than leaning, bouncing or pulsing. Over the small range tested, 7.62-11.43 mm, smaller outlet radii injectors were, in general, more uniform than larger radii injectors, particularly if the gas post was also small. Finally, sharp-edged separating lips were found to produce particularly unstable sprays, especially in terms of pulsing behavior. Designers should not try to minimize lip height as a way to achieve a stable, uniform spray.

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