The Effect of Doublet Injector Orifice Geometry on Spray Characteristics

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Abstract
Doublet injectors have been studied parametrically in past work focusing on, for example, orifice length to diameter ratio, impingement angle, and injection velocity. The effect of orifice geometry has been comparatively under-studied although it has a significant impact on the impinging jet stream dynamics. Few works have been presented since the inception of orifice geometry studies for doublet injectors, yet the findings on the effectiveness of non-circular orifices have been acknowledged since the 1970’s. Of particular promise is the use of rectangular orifices. Many initial drawbacks of non-circular orifices have since been remedied, for example, the precise design and manufacture of the orifice shapes. Yet little work has been done recently to affirm the benefits of rectangular geometries. As a result, the present study examines the effect of changing orifice geometry of doublet injectors on the resulting spray characteristics. Circular geometries are compared to rectangular orifices of varying aspect ratio. The effect of the orifice geometries on Sauter mean diameter, span, fuel and oxidizer mixing, and spray velocity vector fields are characterized for various test conditions. Injection velocity and impingement angle were varied to provide results for different cases. Data were collected at four downstream locations using multiple laser diagnostic systems to provide spray-averaged results. The results indicate affirms that improved mixing efficiency can be achieved through using rectangular orifices over circular orifices. Finer atomization can also be produced through the use of rectangular orifices, but greater droplet size non-uniformities can be present. The rectangular jet streams show greater stream instability compared to circular jet streams, possibly due to the axis-switching phenomenon, which can lead to increased mis-impingement for rectangular orifices depending on the conditions and impingement distance.

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Introduction

Like- and unlike-doublet injectors are used commonly within rocket engines as a means to deliver atomized fuel and oxidizer into the combustion chamber. Hypervigolic fuels are often used with these injectors and rely on a well-mixed spray. In order to improve efficiency, and to reduce harmful emissions or degradation, understanding the cold-flow spray characteristics generated by impinging liquid jets from doublet injectors is paramount. These spray characteristics depend on different flow or geometric conditions including, but not limited to, orifice diameter, orifice length to diameter ratio \((L/d_0)\), impingement angle, jet velocity, and orifice geometry.

In recent decades, many workers have investigated the effect of various parameters on spray performance. However, the effect of orifice shape on spray characterization has been comparatively understudied. Conventionally, rocket injector designs use circular orifices due to ease of machining and economic viability. One of the first studies to directly study the effect of orifice shape on impinging jet injectors was by McHale and Nurick [1]. The work represented an extensive four phase investigation on the effect of non-circular orifice holes on spray characteristics and performance through cold-flow and hot-fire testing. Focus was placed on rectangular and triangular orifices which encompassed different shape geometries and aspect ratios. For practical \(L/d_0\) values \((L/d_0<10)\), non-circular shapes were shown to be less sensitive to hydraulic flip. Further, it was found that both atomization and mixing could be improved with the rectangular shape compared to a circular shape. This was present over many flow cases. High levels of mixing were possible regardless of orifice length ratios for rectangular orifices whereas mixing was a strong function of the orifice diameter ratio for circular orifices. For unlike-doublets, circular orifices generated larger drop sizes compared to non-circular orifices, potentially due to the inability of circular injectors to produce full stream impingement. Improved mixing for non-circular shapes was also demonstrated by Hoehn [2], who attributed the result to a more fully developed flow.

One particular phenomenon present when flow exits a rectangular orifice is axis-switching. Contrainventing vortices forming in the corners of rectangular orifices were highlighted by Yu et al. [3] which may be a cause of the axis-switching phenomenon. For use with impinging liquid jets, great care must be taken to ensure the streams have full area impingement. Also, due to the oscillatory behavior in the stream geometry, the streams can be made to impinge with different cross-sectional shapes. Due to the inherent instability of a turbulent flow exhibiting the axis-switching phenomenon, misimpingement is a greater problem for non-circular orifices than for circular orifices.

Sharma and Fang [4] recently looked into the break-up of liquid jets from non-circular orifices. Their work covers and analyzes various orifice shapes and their effect on jet break-up. The non-circular jets were shown to enhance unstable behavior which therefore produced a faster break-up process. They were also able to demonstrate that only the rectangular orifices displayed axis-switching whereas the square, triangular, and circular orifices did not. Moreover, the results suggest that all non-circular geometries induce greater instabilities and cause faster disintegration.

Most recently, Zhao et al. [5] studied sheet characteristics generated by liquid streams emanating from elliptical orifices. Fu et al. [6] investigated the effect of orifice geometry on impinging jets using gelled simulants. Although mainly qualitative results were provided, enhanced entrainment and mixing properties were seen with square jets. This was attributable to the corner vortex feature in rectangular jets. This also increases the jet instabilities and, therefore, the liquid sheet instabilities which can improve atomization.

The majority of studies utilizing injectors have used circular orifices. Surprisingly, many of the works on non-circular orifices highlight their benefits, particularly when it comes to improved mixing. Yet, a clear lack of studies on the effect of orifice geometry on impinging jet injectors is evident. The preliminary work by McHale, Nurick, and Hoehn has not been replicated or expanded on publicly. Several recent works acknowledge their non-circular orifice studies and the benefits of employing a non-circular orifice. With the advent of laser diagnostics, such as planar laser-induced fluorescence, phase Doppler interferometry, and laser diffraction particle sizing, a greater insight into the effect of orifice geometry on sprays generated by doublet injectors can be achieved, which is the objective of the present study.

Experimental Apparatus and Test Conditions

For the experimental setup, each injector had a removable nozzle allowing for various orifice geometries and designs to be tested. A schematic of the doublet injector setup and an example nozzle geometry is shown in Figure 1. Data were taken at various z-locations, with the convention of, for example, “Z25mm” to indicate the measurement location at 25 mm below the impingement point. The injectors were mounted onto a plate which allowed the impingement angle, 20°, to be varied in 10° increments. Injection velocities of between 8 m/s and 19 m/s were selected to be tested at the different impingement angles. Four orifice geometries were designed to give three like-doublet and three unlike-doublet configurations.

The designed orifices are described in Table 1 and Table 2.
The labels of the different configurations are used as reference when presenting various results.

Planar laser-induced fluorescence (PLIF), 3D phase Doppler interferometry (PDI), and laser diffraction systems were applied to acquire both qualitative and quantitative data on the spray characteristics. PLIF was used to characterize the extent of the mixing between the fuel and oxidizer streams. PDI was used to take point-wise three-dimensional measurements of droplet velocities and droplet sizing. Additionally, a Malvern laser diffraction system was used to take line-of-sight measurements across the spray width to find droplet sizing data. Schematics of the setups of the PLIF, PDI, and laser diffractions systems are shown in Figure 2 to Figure 4.

For this study, water was used as a simulant. Water properties were taken at nominal room temperature values at 25°C. Reynolds number (Re) was varied from 4,488 to 10,502 and Weber number (We) was varied from 513.5 to 2,054. Additionally, impingement angles of 60° and 70° were tested for the six orifice configurations at three injection velocities.

In terms of geometry, six orifice configurations, three like and three unlike pairs, were tested. For each

<table>
<thead>
<tr>
<th>Orifice Shape</th>
<th>Dimensions</th>
<th>AR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circle</td>
<td>0.584 mm Ø</td>
<td>-</td>
</tr>
<tr>
<td>Circle</td>
<td>0.427 mm Ø</td>
<td>-</td>
</tr>
<tr>
<td>Rectangle</td>
<td>0.556 mm × 0.483 mm</td>
<td>1.15</td>
</tr>
<tr>
<td>Rectangle</td>
<td>0.627 mm × 0.427 mm</td>
<td>1.47</td>
</tr>
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</table>

Table 1. Designed orifice geometries.

<table>
<thead>
<tr>
<th>Like</th>
<th>Unlike</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
<td>Circular</td>
</tr>
<tr>
<td>0.427 mm Rectangular</td>
<td>Rectangular</td>
</tr>
<tr>
<td>0.483 mm Rectangular</td>
<td>Mixed</td>
</tr>
</tbody>
</table>

Table 2. Injector orifice configurations.
pair, two impingement angles were examined. Each impingement angle had three $We$ conditions. At each of these $We$ conditions, high-speed video (HSV) was taken of the entire spray, PLIF was applied to each z-location, Malvern instrumentation was applied through the entire width of the spray at each z-location, and the PDI system was applied throughout half of the spray plane at each z-location. The Malvern took data in 5 mm intervals across the spray width and the PDI system took data in a mesh of points with 5 mm separation through half of the spray plane. As all sprays generated were nominally symmetric, and due to how time-intensive collecting PDI data was, half of the spray plane was investigated and mirrored to represent the entire spray plane of interest. Also, due to the time-intensive nature of taking PDI data, only the $V = 16$ m/s case was investigated using the diagnostic.

Results and Discussion

First, the axis-switching phenomenon was investigated qualitatively to see the effect the orifice shape had on the free stream. HSV was used to investigate this in both laminar and turbulent flow. Laminar flow, with $Re = 1300$, and three turbulent conditions were imaged to analyze the extent of the axis-switching phenomenon. Laminar flow just downstream of the exit orifice for the 0.584 mm circular and both rectangular orifices are shown in Figure 5. The circular stream exhibits a uniform cross-section throughout. The rectangular streams, however, display bulging and non-uniformities throughout the stream. The 0.427 mm rectangular stream displays the greatest change in its cross-section, indicating a more pronounced effect from contrarotating vortices in the orifice and greater instability. This is seen, to a lesser extent, in the 0.483 mm rectangular stream.

As the flow enters the turbulent regime, there is less visual distinction between the streams. Although the axis-switching phenomenon is still present in the turbulent streams, it was not imaged with sufficient clarity to quantify behavior, and, hence, are omitted here. The laminar flow does show the physical differences on the free streams and can give insight into possible misimpingement. For the circular stream, the absence of non-uniformities greatly increases the chance for full stream impingement and stream stability. On the other hand, the rectangular orifices show oscillatory behavior which makes them prone to misimpingement due to increased difficulty of having two unsteady streams impinge with the same cross-sectional shape. Analysis of the direct impact of the axis-switching phenomenon on spray characterization is beyond the scope of this work and, as such, was not investigated. Identifying the presence of the phenomenon can help the understanding of results between the different orifice shapes.

Example PLIF results are shown in Figure 6. This figure shows the difference in relative spatial distribution of the fuel and oxidizer for planar spray sheets located at $Z40$mm generated from a $70^\circ$ impingement angle at 16 m/s for the three like-configurations. These figures find the locations in the sheet with fuel dominance, marked by the red peaks, and oxidizer dominance, marked by the blue peaks. It should be noted that these are relative values and, as such, do not give a direct indication of the mixing performance but, instead, highlight fuel and oxidizer location. Using these images, the mixing efficiency, $\eta_m$, was calculated, as shown in each subfigure, where a value of 100% indicates a perfectly mixed spray plane. Therefore, the level of mixing performance of the circular orifice spray is lower than both of the rectangular orifice sprays, with the 0.427 mm rectangular orifice spray producing the highest mixing performance.

Of interest to note is the spray shape. Both the circular and 0.483 mm rectangular orifice planes display fairly good symmetry. This is not the case for the 0.427 mm rectangular orifice which shows greater mixing asymmetry, potentially due to misimpingement from the increased effect of the axis-switching phenomenon. Yet, with this asymmetry, the 0.427 mm rectangular orifice spray plane exhibits the highest mixing efficiency.
Figure 6. PLIF results at $\theta = 70^\circ$, $V = 16$ m/s at Z40mm of (left) 0.584 mm circular orifice, (center) 0.483 mm rectangular orifice, and (right) 0.427 mm rectangular orifice.

Table 3. Spray-averaged mixing efficiencies at corresponding like orifice configuration and injection velocity.

<table>
<thead>
<tr>
<th>Orifice Configuration</th>
<th>$2\theta = 60^\circ$</th>
<th>$2\theta = 70^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8 m/s</td>
<td>12 m/s</td>
</tr>
<tr>
<td>Circular</td>
<td>77.45%</td>
<td>82.80%</td>
</tr>
<tr>
<td>0.483 mm Rectangular</td>
<td>77.65%</td>
<td>80.04%</td>
</tr>
<tr>
<td>0.427 mm Rectangular</td>
<td>82.92%</td>
<td>73.38%</td>
</tr>
</tbody>
</table>

Figure 7. PLIF results at $\theta = 70^\circ$, $V = 16$ m/s at Z40mm of (left) circular, (center) rectangular, and (right) mixed orifices.

Table 4. Spray-averaged mixing efficiencies at corresponding unlike orifice configuration and injection velocity.

<table>
<thead>
<tr>
<th>Orifice Configuration</th>
<th>$2\theta = 60^\circ$</th>
<th>$2\theta = 70^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8 m/s</td>
<td>12 m/s</td>
</tr>
<tr>
<td>Circular</td>
<td>69.64%</td>
<td>80.20%</td>
</tr>
<tr>
<td>Rectangular</td>
<td>64.94%</td>
<td>79.71%</td>
</tr>
<tr>
<td>Mixed</td>
<td>81.12%</td>
<td>77.98%</td>
</tr>
</tbody>
</table>
Spray plumes are notoriously turbulent and, hence, the planar mixing results can be potentially misleading. For example, it is possible that a near-perfectly mixed spray plane can appear at one particular downstream location but the rest of the spray does not exhibit the same performance. Therefore, to account for this, the mixing efficiency was found for each downstream location and then averaged to provide a spray-averaged mixing efficiency.

Table 3 shows the spray-averaged mixing efficiencies for the 60° and 70° impingement angle cases of the like-configurations. For example, the spray-averaged mixing efficiency for the circular orifice configuration with a 60° impingement angle and an injection velocity of 8 m/s is 77.45%. For all like orifice configurations, except one, the mixing efficiency improves as injection velocity increases. There is no clear trend for mixing efficiencies for the 60° case, particularly for \( V = 16 \) m/s where the mixing is fairly equal for all orifice configurations. However, for the 70° case, the circular orifice configuration exhibits the lowest mixing performance for each tested injection velocity. In two of the cases, the 0.427 mm rectangular orifice displays the highest mixing efficiency. This indicates that improved mixing performance can be achieved through utilizing rectangular orifices over circular orifices for an impingement angle of 70°.

Example PLIF results for the unlike-configurations are shown in Figure 7. One main difference between the PLIF images is in the spray shape. The rectangular case is fairly symmetric and straight, similar to the like-configurations, but the circular and mixed cases exhibit a curved shape. This curving can be attributed to not having full stream impingement due to the oxidizer orifice having a larger cross-section than the fuel orifice. Although the oxidizer orifice for the rectangular case also has a larger cross-section, it is not sufficient enough to affect the spray shape. The small fuel stream impinges in the center of the oxidizer stream causing a region of full impingement, however, the edges of the oxidizer stream has reduced impingement or has no impingement at all. From this, the oxidizer stream can be seen to split into two and to wrap around the fuel stream, creating the distinctive curved shape. Also, from looking at the oxidizer and fuel dominance in the images, it is clear that there is more oxidizer dominance away from the center of the y-location of the spray plane, which is to be expected. The majority of the fuel is found in the center of the y-location. The rectangular case does not exhibit these same properties, but it shows the oxidizer and fuel dominant regions being unaligned, with more oxidizer in the top half of the y-location and more fuel in the lower half of the y-location. This may be due to misimpingement where, from impinging two rectangular streams which are both subject to non-similar axis-switching effects, the oxidizer and fuel streams offset from each other.

Spray-averaged mixing efficiencies for the unlike cases can be found in Table 4. There are few clear trends with these results, which highlights potential increased spray instability and non-full impingement. Interesting to note is that mixing efficiency does not consistently improve with an increase in injection velocity. For both impingement angles for the mixed case, an increase in injection velocity from 8 m/s to 12 m/s causes the mixing efficiency to decrease. At 12 m/s the spray is in the transition stage approaching a fully developed spray which could have a greater effect on the mixed case. Additionally, the mixed case has the least overall change in mixing efficiency between the scenarios, indicating it could be less sensitive to the changed parameters than the other cases.

Here, increasing the impingement angle does not generally improve the mixing efficiency, which was found for the like-configurations. Further, comparing the like- and unlike-configurations, the like-configurations generally have improved mixing efficiency over the unlike cases.

Spray-averaged SMD and span values were taken using Malvern instrumentation at different \( We \) and are shown in Figure 8 and Figure 9 for the like-configurations. From Figure 8, the spray-averaged SMD decreases as \( We \) increases for all cases. The 70° impingement angle also shows a greater SMD reduction over the 60° impingement angle cases for all scenarios. Investigating only the 60° impingement angle shows that the circular orifice has the highest SMD whilst the 0.427 mm rectangular orifice exhibits the lowest SMD. For the 70° case, there is a similar trend with the circular orifice exhibiting the highest SMD, but this is much less pronounced than for the 60° case.

For Figure 9, the span values increase with \( We \). Further, the 60° impingement angle produces a span closer to unity over the range of \( We \) than the 70° angle, with the 60° circular orifice case showing generally the least polydispersity. However, for the 70° configuration, there is little trend on the effect of orifice configuration on span value.

The spray-averaged SMD and span Malvern results for the unlike-configurations are shown in Figure 10 and Figure 11. For the SMD results, again, the SMD values decrease with increase in \( We \). The unlike-rectangular configuration produces the highest SMD for both impingement angles, while the circular configuration produces the lowest SMD for both impingement angles. This shows that the effect of impingement angle is not as significant as other parameters, whereas the impingement angle proved to be more significant for the like-configurations. For the span results, all configurations display an increase in span as \( We \) is increased. At a \( We \) of 500, all values are about equidistant from unit span so have roughly equal non-uniformity. As \( We \) is increased,
Figure 8. Spray-averaged SMD values for different like-configurations and *We* with an impingement angle of (left) 60° and (right) 70°.

Figure 9. Spray-averaged span values for different like-configurations and *We* with an impingement angle of (left) 60° and (right) 70°.
Figure 10. Spray-averaged SMD values for different unlike-configurations and $We$ with an impingement angle of (left) 60° and (right) 70°.

Figure 11. Spray-averaged span values for different unlike-configurations and $We$ with an impingement angle of (left) 60° and (right) 70°.
the rectangular case has the most uniform spray up to a point, but the rate of non-uniformity increase is very large compared to the other configurations.

Using PDI allowed for point-wise measurements of three-dimensional droplet velocity. Figure 12 shows the velocity vector field when looking onto the y-z plane for the various like orifice configurations with a 70° impingement angle and an injection velocity of 16 m/s. Each graph displays the velocity measurements taken at the different downstream locations and at various x- and y-locations. Therefore, although a two-dimensional image is presented, the results produced are three-dimensional. Each case has a similar maximum droplet velocity of just over 15 m/s, and a similar number of data points collected. Of most interest here is the change in droplet absolute velocity as the downstream location increases. For the circular orifice, for example, the 25 mm z-location displays the highest absolute velocity and, as the downstream location is increased, the absolute velocity noticeably decreases. This is untrue for both rectangular cases, where the center of the spray retains relatively high absolute velocity droplets (> 14 m/s) for all downstream locations. The change in centerline droplet velocity as downstream location is increased for the different like cases is shown in Figure 13. With this, however, there are an increased number of low absolute velocity vectors (< 6 m/s). This is potentially due to misimpingement. The circular orifice produces full impingement and so there is a gradual and uniform decrease in droplet velocity as the downstream location is increased. For the rectangular cases, however, where misimpingement is more likely, there is not full impingement so it is possible for a concentrated stream of high velocity droplets to be fairly undisturbed as the downstream location is increased.

Figure 14 displays the velocity vector field for the unlike-configurations. In comparison to the like-configurations, the unlike-configurations have a larger dissimilarity for the 70° impingement angle and 16 m/s injection velocity case. Whilst the maximum droplet absolute velocity recorded is similar, there is a clear divergence in similarity for the minimum absolute velocity recorded. For example, for the rectangular case, the minimum droplet absolute velocity is around 7 m/s whilst it is 4 to 5 m/s for the other cases. Both the circular and mixed cases, however, have and maintain higher droplet velocities at the center of the spray. These cases also have the largest orifice dimension difference for the impingement width. It is possible, therefore, that due to having one stream not experience full impingement, the center of the spray sees two streams of high velocity, whilst the edges of the spray do not. As there is less variance in droplet velocities for the rectangular case, this can be attributed to having the closest to full impingement as the orifice dimensions are the most similar.

Summary and Conclusions

The effect of changing orifice geometry on spray characterization for like- and unlike-injectors was investigated. Various diagnostic techniques were used to take measurements and to analyze the effects orifice geometry, impingement angle, and injection velocity had on the spray characteristics.

For multiple conditions, both like-rectangular configurations exhibited reduced SMD and improved fuel and oxidizer mixing compared to the like-circular configuration. However, in general, the like-circular configuration had reduced spray polydispersity. Both the reduced SMD and increased span of the like-rectangular configurations may be attributed to a more dynamically unstable jet stream, in part due to the axis-switching phenomenon. The 0.427 mm rectangular orifices, which have the highest AR, have the lowest SMD for most test cases. Alongside this, it displays the greatest spray asymmetry in shape, SMD, and span values. This indicates that higher AR rectangular orifices may produce a finer spray but its asymmetry and non-uniformities are increased. The like-circular configuration also displays a more uniform and gradual decrease in droplet absolute velocity across the entire spray plume. The like-rectangular configurations both exhibit larger droplet absolute velocity fluctuation across much of the spray plume. The non-uniformities in SMD, span, droplet absolute velocity, and shape for the like-rectangular configurations detail the increased spray instability compared to the like-circular configuration. This may influence the accuracy and usefulness of the spray-averaged like-rectangular results.

While clear trends are evident for the like-configuration results, the same is not seen for the unlike-configurations. The unlike-circular, -rectangular, and -mixed configurations all show the highest, or lowest, mixing efficiency for a particular test condition. For both impingement angles, the unlike-rectangular configuration had the highest spray-averaged SMD and, for most cases, the unlike-circular configuration had the lowest spray-averaged SMD. Although, for the like-configurations, the rectangular orifices produced the lowest SMD, the opposite is seen for the unlike case. The effect of impingement angle is small on the SMD and span values. This may be due to non-full stream impingement which may have a larger effect on the SMD and span values. For higher injection velocities, the unlike-rectangular configuration displays greater non-uniformities in droplet size and droplet absolute velocity throughout the spray plume.

These findings closely relate to the results found by McHale and Nurick in the 1970’s. These results strengthen the findings that rectangular orifices can be used to improve mixing and produce finer atomization, yet it is evident that further study is needed.
Figure 12. Three-dimensional velocity vector field of \( \theta = 70^\circ \), \( V = 16 \text{ m/s} \) case of (a) circular, (b) 0.483 mm rectangular, and (c) 0.427 mm rectangular orifice configurations.

Figure 13. Decrease in centerline velocity with downstream location for like-configurations with an impingement angle of (left) 60° and (right) 70°.
Figure 14. Three-dimensional velocity vector field of $\theta = 70^\circ$, $V = 16$ m/s case of (a) circular, (b) rectangular, and (c) mixed orifice configurations.
Nomenclature
\( AR \) aspect ratio
\( d \) orifice diameter
\( L \) orifice length
\( Re \) Reynolds number
\( V \) injection velocity
\( We \) weber number

\( \eta_m \) mixing efficiency
\( 2\theta \) impingement angle

Subscripts
\( o \) orifice

References