Effects of Injector Design and Impingement Techniques on the Atomization of Self-Pressurizing Oxidizers

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Use of nitrous oxide as a hybrid rocket oxidizer is currently on the rise due to its attractive self-pressurizing properties. However, little is known about the design and performance of nitrous oxide injectors, resulting in high levels of uncertainty when it comes to hybrid rocket performance predictions. A new facility has been developed at Stanford University for the characterization of nitrous oxide injector atomization and vaporization using high speed video photography. A description of the new test apparatus is presented in this paper, along with details of the initial experiments using carbon dioxide as a fluid analog to nitrous oxide. Preliminary test results suggest that the injector hole diameter and length to diameter ratio can significantly impact atomization characteristics, while the injector inlet geometry has only a minor effect. Initial results also show that an impinging injector design can be significantly more effective at atomizing high vapor pressure propellants than a nonimpinging single hole design.

Nomenclature

\[ D = \text{injector hole diameter} \]
\[ h_f = \text{latent heat of vaporization} \]
\[ Ja = \text{Jakob number} \]
\[ L = \text{injector hole length} \]
\[ M = \text{molecular weight} \]
\[ P = \text{pressure} \]
\[ T = \text{temperature} \]
\[ u = \text{liquid jet velocity} \]
\[ We = \text{Weber number} \]
\[ x_i = \text{impingement distance} \]
\[ Z = \text{compressibility factor} \]

Subscripts

1 = location upstream of injector
2 = location downstream of injector
c = downstream chamber
crit = critical conditions
inj = pre-injector volume
\[ L = \text{liquid} \]
\[ S = \text{saturated state} \]
\[ V = \text{vapor} \]

Symbols

\[ \omega = \text{acentric factor} \]

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\[ \phi = \text{density ratio correction} \]
\[ \rho = \text{density} \]
\[ \sigma = \text{surface tension} \]
\[ \theta = \text{included impingement angle} \]

**I. Introduction**

In recent years, multiple full scale hybrid rocket development programs have utilized nitrous oxide as a liquid oxidizer. Nitrous oxide is an attractive oxidizer choice due to its self-pressurizing characteristics (i.e. high vapor pressure at moderate temperatures), along with its relative safety compared to other oxidizers. However, to date there have been only limited efforts in the characterization of nitrous oxide delivery systems for hybrid rockets, including the topics of tank pressurization and injector design. Specifically, the design of an injector can have a dramatic effect on the overall efficiency and stability of a hybrid rocket system. A properly designed injector should provide the appropriate propellant mass flow rate to the combustion chamber, while sufficiently atomizing the liquid jet into small droplets.

Liquid propellant injectors usually operate by either the mechanical breakup or flash atomization of a liquid jet. The mechanical breakup mode is dominated by aerodynamic and viscous effects, wherein an unstable jet forms a droplet spray. Flash atomization can occur when a liquid jet becomes metastable in a superheated state due to the sudden pressure drop across the injector. With sufficient superheat and the presence of bubbles or nucleation sites, the jet can break up in a more violent manner due to rapid bubble growth, often resulting in sprays of much finer droplets than observed in the mechanical breakup mode (allowing for rapid evaporation and mixing). For traditional liquid propellants (e.g. LOX, hydrogen peroxide, kerosene, etc.), these different atomization regimes have been relatively well studied, due to their extensive use in the liquid rocket industry, in addition to the fact that they can often be treated as incompressible in the liquid phase, and as ideal gases in the vapor phase. This is not the case for the high vapor pressure propellant nitrous oxide, which is typically used as a compressible liquid.

In 1986, Kitamura et al. studied the transition between the mechanical breakup mode and flash atomization for superheated water and ethanol, and more recently Cleary et al. extended this analysis to describe a flashing transition region. Correlations for critical superheating was presented based upon two dimensionless thermodynamic parameters, the vapor Weber number, \( We_V \), and the Jakob number, \( Ja \), as well as a density correction factor, \( \phi \), each defined in Eqns. (1-3) below.

\[ We_V = \frac{\rho_V u^2 D}{\sigma} \]  
\[ Ja = \frac{\rho_L c_{p,L} (T - T_S)}{\rho_V h_{fg}} \]  
\[ \phi = 1 - \exp \left( -\frac{2300 \rho_V}{\rho_L} \right) \]

where \( u \) is the liquid jet velocity, \( D \) is the hole diameter, \( \sigma \) is the liquid surface tension, \( c_{p,L} \) is the specific heat of the liquid, \( T \) is the liquid temperature, \( T_s \) is the saturation temperature corresponding to the downstream pressure \( P_2 \), and \( h_{fg} \) is the latent heat of vaporization. The liquid density, \( \rho_L \), is based on the liquid flowing into the injector, while the vapor density, \( \rho_V \), is calculated for the conditions just downstream of the injector. The Weber number represents the ratio of the inertia of a fluid to its surface tension, and is often used in the characterization of liquid jet sprays. Hence, there does not seem to be a clear physical basis for using the vapor Weber number in these correlations versus the liquid Weber number. The Jakob number is the ratio of sensible to latent enthalpy released by a fluid during the phase change from liquid to vapor. The correlations presented Kitamura and Cleary are plotted in Fig. 1 below. While quite useful for some applications, these correlations are limited to Weber numbers of approximately 25 or lower, meaning they are not applicable to most rocket systems using liquid nitrous oxide injectors (Weber numbers greater than \( 10^4 \) are common due to high flow velocities and low surface tension).
Unfortunately, nitrous oxide injector design is not well understood due to a lack of heritage, as well as the difficulties in modeling associated with non-ideal compressibility effects (compressibility factor $Z \sim 0.13$ for saturated liquid, $Z \sim 0.53$ saturated vapor). Work in 2007 by Dyer et al. addressed the compressible liquid and real gas effects in the modeling of two-phase injectors for self-pressuring oxidizers\textsuperscript{5}. Their model demonstrates good agreement with regards to mass flow rate, specifically in comparison to measurements from sub-scale hybrid rocket tests for a variety of injector designs. However, as of yet, there have not been adequate studies into the modeling and experimental testing of nitrous oxide injector designs with regard to atomization characteristics. It is standard practice in the development of hybrid rockets to perform cold flow testing (oxidizer flow only, no ignition) in order to characterize a given injector design in terms of mass flow rate and atomization. However, most cold flow tests are not performed at the actual operating pressures observed during combustion testing. Of particular importance is the pressure drop $\Delta P$ across the injector, which is the difference between $P_1$ and $P_2$, the pressures immediately upstream and downstream of the injector, respectively. Cold flow testing typically results in a much larger $\Delta P$ than would be expected during tests involving combustion, which is a concern when it comes to understanding the mechanisms for atomization and vaporization of liquid jets. This paper describes a new facility for the cold flow testing and visualization of nitrous oxide injector designs at realistic operating pressures, and presents some of the initial visualization results.

II. Experimental Setup

In order to characterize the breakup modes and atomization characteristics of different injector designs, a new facility has been developed to allow for the visualization of oxidizer flow fields just upstream and downstream of an interchangeable injector plate. Transparent polycarbonate tubes closed on each end by aluminum end caps act as pressure vessels while providing optical access to the flow field created by the injector. The goal of this setup is to allow for the observation of the atomization process at realistic operating pressures downstream of the injector, while keeping track of the flow conditions upstream of it. A cut-away model of the optical test section along with a photo of the assembled hardware are shown in Fig. 2 below. A high-speed camera is used to record video of the flow field at frame rates ranging from 300 to 1200 frames per second. A laser sheet is employed to illuminate the center plane of the flow using standard 532 nm laser pointer and a borosilicate glass rod 3 mm in diameter. Additionally, pressure and temperature are measured in both the upstream and downstream polycarbonate chambers at sampling rates from 500 Hz up to 1,000 Hz.

Figure 1. Correlations of critical Jakob and Weber numbers as developed by Kitamura and Cleary et. al\textsuperscript{3,4}.
Although nitrous oxide has properties that make it an attractive oxidizer choice for hybrid rockets, there are still significant risks associated with its use. Specifically, nitrous oxide has a positive heat of formation, and the potential exists for rapid decomposition under certain conditions. These runaway decomposition reactions can lead to violent and dangerous pressure vessel failures. Multiple groups have studied these explosive events, and have concluded that despite the potential hazards, nitrous oxide can be used safely with proper handling considerations. However, in order to minimize safety risks as well as simplify operating procedures, carbon dioxide will be used as an analog to nitrous oxide for these tests. Nitrous oxide and carbon dioxide are quite similar thermodynamically, in that they have almost exactly the same molecular weight and exhibit less than 5% variation in thermodynamic properties at the critical condition, as shown in Table 1. Therefore, it is expected that injector tests utilizing carbon dioxide will do a reasonable job replicating the atomization characteristics of nitrous oxide. However, due to the difference inacentric factor of carbon dioxide and nitrous oxide, properties such as saturated vapor pressure and vapor density can differ upwards of 15% nearing the critical point, as shown in Fig. 3 (though the saturated liquid density matches quite closely). The differences in thermodynamic properties of nitrous oxide and carbon dioxide could have noticeable effects on the dynamics of atomization, and this fact will be considered during data analysis. If necessary, future testing will be extended to the use of nitrous oxide to assess the validity of using carbon dioxide as an fluid analog.
Table 1. Comparison of important thermodynamic properties of $N_2O$ and $CO_2^{7-10}$

<table>
<thead>
<tr>
<th>Property</th>
<th>Nitrous Oxide ($N_2O$)</th>
<th>Carbon Dioxide ($CO_2$)</th>
<th>Percent Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$ (amu)</td>
<td>44.013</td>
<td>44.010</td>
<td>-0.007</td>
</tr>
<tr>
<td>$P_{crit}$ (MPa)</td>
<td>7.251</td>
<td>7.377</td>
<td>+1.738</td>
</tr>
<tr>
<td>$T_{crit}$ (K)</td>
<td>309.6</td>
<td>304.2</td>
<td>+1.744</td>
</tr>
<tr>
<td>$\rho_{crit}$ ($kg/m^3$)</td>
<td>452.0</td>
<td>467.6</td>
<td>+3.451</td>
</tr>
<tr>
<td>$Z_{crit}$</td>
<td>0.273</td>
<td>0.274</td>
<td>+0.366</td>
</tr>
<tr>
<td>$\omega$</td>
<td>0.160</td>
<td>0.225</td>
<td>+40.625</td>
</tr>
</tbody>
</table>

Figure 3. Percent difference in saturated vapor density, liquid density, and vapor pressure ($P_S$) for $CO_2$ as an analog to $N_2O$. (Oxidizer temperatures ranging from 250 K to 290 K are of particular interest for large scale hybrid rocket systems using $N_2O^{7-10}$.)

Liquid carbon dioxide is supplied to the test section by a small pressure vessel that is also made from polycarbonate tube and aluminum end caps. This vessel acts as an intermediate run tank between the test section and the industrial compressed gas cylinders that the carbon dioxide is delivered in. The run tank also provides optical access because it is currently used for experiments investigating the expulsion dynamics of self-pressurized propellant tanks. More information on the experiments performed with the run tank can be found in work performed by Zimmerman et al. during 2012.” The liquid carbon dioxide flows between tanks and to the test section through 6.4 mm diameter stainless steel tubing, and high pressure flexible hose. A pneumatically driven pump is used to fill the run tank before each test. The tank is equipped with the ability to pressurize the liquid carbon dioxide above its saturation pressure (a.k.a. supercharging) with compressed helium. This supercharging serves to limit any cavitation in the feed line and to set the appropriate run conditions for the optical test section, specifically the upstream chamber or pre-injector volume. Helium is chosen for supercharging because it does not readily dissolve in nitrous oxide or carbon dioxide. Additionally, high pressure helium or nitrogen is used to pre-pressurize the downstream section to achieve the desired run conditions. A process and instrumentation diagram (P&ID) with more details on the fluid handling and instrumentation of the system can be found in Fig. 4. Pressure and temperature measurements are made in both the pre-injector volume and the downstream chamber, allowing for the instantaneous measurement of $\Delta P$ and supercharge pressure, as well as a host of other fluid dynamic properties. An LED is precisely controlled and placed within the camera’s field of view in order to facilitate the synchronization of high speed video with pressure and temperature data, and the creation of individual flow images overlayed with time-dependent flow information.
Figure 4. Process and instrumentation diagram (P&ID) for injector and tank testing facilities
To allow for the testing of a wide range of injector designs, the injector insert was designed to be easily interchangeable. The insert is mounted within an aluminum block that serves as the junction between the upstream and downstream polycarbonate tubes as shown in Fig. 2. Silicone O-rings are used to provide adequate sealing at each of the polycarbonate and aluminum junctions. An assortment of injector inserts have been manufactured for initial testing in the optical testing facility. This first set of injectors have been designed to investigate the atomization characteristics of injectors with varying hole diameter, \( D \), and hole length to diameter ratio, \( L/D \), as well as the effect of injector hole entrance geometry (square edge, rounded, chamfered etc). During initial testing, the length, \( L \), of each injector hole is fixed at a typical injector plate thickness of approximately 18.4 mm. Future testing will allow for the variation of the injector insert thickness and hole length. The specific geometries of each injector insert are outlined in Table 2, and cross-sections of each are shown in Fig. 5. All of the single hole injector inserts are manufactured using brass, a metal commonly used in hybrid rocket injectors due to its heat transfer characteristics and machinability.

<table>
<thead>
<tr>
<th>Number</th>
<th>Style</th>
<th>( D ) (mm)</th>
<th>( L/D )</th>
<th>Entrance Geometry</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>Single</td>
<td>1.50</td>
<td>12.3</td>
<td>Square Edge</td>
<td>Brass</td>
</tr>
<tr>
<td>(2)</td>
<td>Single</td>
<td>1.50</td>
<td>12.3</td>
<td>Rounded</td>
<td>Brass</td>
</tr>
<tr>
<td>(3)</td>
<td>Single</td>
<td>1.50</td>
<td>12.3</td>
<td>Chamfered</td>
<td>Brass</td>
</tr>
<tr>
<td>(4)</td>
<td>Single</td>
<td>0.79</td>
<td>23.3</td>
<td>Square Edge</td>
<td>Brass</td>
</tr>
<tr>
<td>(5)</td>
<td>Impinging</td>
<td>1.50</td>
<td>12.3</td>
<td>Rounded</td>
<td>Accura 60 Rapid Prototype</td>
</tr>
</tbody>
</table>

Interesting work performed in 1992 by Kuo et al. suggests that like-on-like impinging injector designs could improve flash atomization\(^\text{12}\). Specifically it was proposed that impinging flash atomizers could result in a wider, more thoroughly atomized spray fan, with finer, more evenly distributed droplets. Like-on-like impinging injectors have seen widespread use in the liquid rocket industry, and the associated atomization properties have been well studied. However, self-pressurized oxidizers such as nitrous oxide are virtually untested in like-on-like impinging injector designs. Therefore, the optical injector test setup will be used to characterize a range of different self impinging doublet designs, varying both the impingement included angle, \( \theta \), and impingement distance, \( x_i \). One of these impinging
injectors was tested during these initial experiments, with its geometry also detailed in Table 2 and Fig. 5. It should be noted that the impinging design tested in these experiments consists of a straight section followed by a bend to establish the impingement angle. This design requires minimal space laterally and allows for a large number of doublets to be placed in a full scale injector. The injector for these experiments has an included impingement angle of 90° and an impingement distance of 2.54 mm. While machining the more complicated geometries from brass is possible, the impinging injector inserts are manufactured using rapid prototyping stereolithography for convenience. Plastic branded as Accura 60 (by 3DSystems) is used and has properties similar to polycarbonate, specifically with regard to strength and stiffness. Fig. 6 shows a photo of one brass injector insert and one impinging plastic injector insert tested during the initial experiments. Future work will compare the results of identical hole designs using both brass and plastic to determine the effect of manufacturing methods and materials on atomization.

![Figure 6. Brass and plastic injector inserts for initial testing with corner O-rings installed.](image)

**III. Results and Discussion**

To date, over 200 tests have been performed in the new injector testing facility, investigating the jet characteristics of 5 different injectors using carbon dioxide. Experiments have been performed over a wide range of chamber pressures and $\Delta P$ values, with chamber pressure ranging from atmospheric conditions up to approximately 7 MPa. In this section, some representative test results are presented, and images from the testing of each injector are compared to one another.

A typical test is prepared by filling the carbon dioxide run tank to a desired fill level. After letting the run tank contents settle to a stable temperature and pressure condition, the downstream chamber and pre-injector volume are pressurized to a predetermined level with compressed helium or nitrogen, and the run tank is supercharged using compressed helium to the desired initial run pressure. An exhaust valve is connected to the downstream section, as shown in Fig. 4, but it remains closed until after the test is completed. Once the desired tank and chamber conditions are met, a pneumatically actuated ball valve located between the tank and the pre-injector volume is opened to initiate a test. During a test, both the pre-injector volume and the downstream chamber gradually increase in pressure. The pressure drop, $\Delta P$, is established as the pressure in the pre-injector volume rises faster than in the chamber. Because the chamber exhaust valve remains closed, at a certain point the chamber pressure begins to catch up with the pre-injector volume until the pressure drop across the injector becomes zero, and the test is completed. This dynamic testing process allows for a sweep of operating pressures during a single test (future work will utilize a back pressure valve to perform tests with steady $\Delta P$ conditions, which should allow for better visualization). Pressure time histories in the pre-injector volume and the chamber are shown for a typical test in Fig. 7 below, where the main ball valve is opened at time $t = 0s$. 
Figure 7. Pressure time histories for the pre-injector volume and downstream chamber for a typical injector test. Injector (2) was used for this test.

During each test, high speed video at 300 frames per second or higher was recorded. After each test, every frame from the video was matched with the corresponding data points. In addition to measuring temperatures and pressures for each of the frames, a venturi flow meter and a Stellar Technologies, Inc. differential pressure transducer were used to calculate mass flow rate. However, a detailed analysis of the system mass flow rate and the characterization of injector discharge coefficients are currently ongoing, and will not be presented in this paper. In order to compare the atomization behavior for these initial experiments, images at various $\Delta P$ values for each injector are shown in Figures 8-12 below. All of these tests were performed at instantaneous chamber pressures ranging from $3.6 \, MPa$ to $4.0 \, MPa$ and supercharge pressures of approximately $350 \, kPa$. Images from these tests demonstrate the flash atomization mode and are characterized by the creation of an aerosol “cloud” of small vaporizing droplets downstream of the injector.

Figure 8. Injector (1) images at (a) $\Delta P = 35 \, kPa$, (b) $\Delta P = 350 \, kPa$, (c) $\Delta P = 700 \, kPa$, and (d) $\Delta P = 1.4 \, MPa$. 

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Figure 9. Injector (2) images at (a) $\Delta P = 35 \text{kPa}$, (b) $\Delta P = 350 \text{kPa}$, (c) $\Delta P = 700 \text{kPa}$, and (d) $\Delta P = 1.4 \text{MPa}$.

Figure 10. Injector (3) images at (a) $\Delta P = 35 \text{kPa}$, (b) $\Delta P = 350 \text{kPa}$, (c) $\Delta P = 700 \text{kPa}$, and (d) $\Delta P = 1.4 \text{MPa}$.
From initial examination of the images in Figures 8-12, it is observed that the jets developed by injectors (1) - (3) are relatively indistinguishable. Slight variations in the diameter and character of the initial jets can be seen as they leave the injectors, likely due to varying internal flow phenomena. Acquisition of higher resolution and more closely zoomed photos is ongoing and will be necessary to resolve these details. It is expected that these internal flow
characteristics depend on both the level of supercharge and the value of $\Delta P$, and will significantly influence the mass flow rate characteristics of a particular injector, and thus the discharge coefficient. When comparing injectors (1) and (4), it is immediately obvious that the jet from injector (4) exhibits less widespread atomization of the jet for a given $\Delta P$, and generally seems to expand at a smaller angle compared to the similarly shaped, but larger orifice of injector (1).

The most interesting results from these initial tests come from those involving the self-impinging doublets used in injector (5). The impinging jets are oriented to lie in a vertical plane that passes through both the camera lens and the polycarbonate tube. It is obvious from examination of Fig. 12 that for a wide range of $\Delta P$ levels, this particular impinging design does a significantly better job atomizing and dispersing the carbon dioxide downstream of the injector. From the above results, the use of like-on-like self impinging injectors is recommended when achieving sufficient atomization is critical or problematic.

Throughout initial testing, the mechanical breakup mode was only observed during tests with both small values of $\Delta P$ and large supercharge pressures simultaneously. These tests indicate that the mechanical breakup mode can dominate for carbon dioxide atomization over a limited range of operating conditions. However, more testing is necessary to develop correlations for the transition from the mechanical breakup mode to flash atomization. Two images of non-flashing injector operation for injectors (2) and (5) are shown in Fig. 13 below, corresponding to a $\Delta P$ of 35 kPa and supercharge pressures of approximately 2 MPa. The non-flashing jets from these images are characterized by some breakup into larger visible droplets, and no apparent aerosol “cloud” as seen in the flashing operation of Figures 8-12. The first image in Fig. 13 corresponds to flow from an injector with a single hole, while the second image is from testing of the impinging doublet injector. As expected, these results suggest that impinging injectors provide improved atomization for non-flashing injector operations, in addition to the flashing jets described previously.

![Figure 13. Images of highly supercharged non-flashing jets using (a) single hole injector (2) and (b) impinging doublet injector (5), both at $\Delta P = 35$ kPa and supercharge pressures of approximately 2 MPa](image-url)
IV. Conclusions and Future Work

A new injector testing facility has been developed to examine the effects of various design parameters on the atomization and mass flow rate characteristics of injectors for use in nitrous oxide systems. For both simplicity and known safety concerns, liquid carbon dioxide is used as a fluid analog to nitrous oxide during testing in this apparatus. Initial results from testing in this facility suggest that injector inlet geometry has a minor effect on the overall atomization characteristics of an injector, but the diameter and $L/D$ ratio of the injector orifices can play a large role in determining the injector atomization performance. Additionally, it has been observed that like-on-like impinging injectors can significantly improve atomization performance and vapor distribution in a combustion chamber for operation in the mechanical breakup mode and by flash atomization.

Flow visualization work is currently ongoing for a variety of different injector hole geometries not discussed in this work, and improvements to the imaging system are underway. Continuing work using this test apparatus is aimed at developing correlations for flash atomization transition based on flow parameters such as the Weber and Jakob numbers. Future work will include the study of mass flow characteristics for a variety of injector designs, specifically focused on mapping the discharge coefficient for each design over a range of operating conditions. Additionally, pressure isolation properties of different injectors will be studied, with a particular interest in the coupling between the oxidizer feed system and combustion chamber.

Acknowledgments

This work is supported by the National Defense Science and Engineering Graduate (NDSEG) Fellowship Program as well as NASA Ames Research Center and the Aeronautics and Astronautics Department at Stanford University. The authors would like to thank Jonah Zimmerman for his dedication, hard work, and countless hours spent working on this project in addition to his own.

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