Measurement of the three-component velocity field inside the combustor section of a scramjet would significantly improve the understanding of this complex flow. Unfortunately, no instantaneous, three-component, spatially resolved velocity measurements in scramjets during fuel combustion are reported in the literature. Stereoscopic Particle Image Velocimetry (SPIV) is an optical measurement technique that is capable of determining three-components of velocity simultaneously with virtually no impact on the flowfield. SPIV has the additional capability of providing instantaneous or time-averaged velocity measurements. In recent years, work has been conducted to apply the SPIV technique to the scramjet combustor facility at the University of Virginia. Particle Image Velocimetry has been used to obtain instantaneous three-component velocity measurements in a scramjet combustor. Some background of the SPIV technique and the experimental assembly are presented along with information about the supersonic combustion facility at UVa. Measured 3D velocity fields and some plots derived from these measured velocity fields are presented. The data obtained shows successful implementation of the SPIV technique to the scramjet combustor at the University of Virginia.
Smith 2

Combustion Facility and the existing direct-connect scramjet combustor installed in the facility. The facility, which is schematically and photographically presented in Figure 1, is an electrically-heated, clean-air supersonic wind tunnel that is capable of simulating flight Mach numbers near 5. This tunnel has continuous flow capability which allows unlimited duration scramjet testing. Importantly, the facility at the University of Virginia is electrically heated and unlike wind tunnels that heat air through combustion, it does not have a freestream that is vitiated with water, carbon dioxide or other contaminants. References 2 and 3 provide further details on the facility. Typical operating conditions are listed in Table 1.

Figure 1: University of Virginia Supersonic Combustion Facility, a) schematic, and b) photograph from above combustor level
Table 1: Typical University of Virginia Supersonic Combustion Facility test conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DMSJ combustor</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>Air</td>
<td>H₂</td>
</tr>
<tr>
<td>Stag. press. (kPa)</td>
<td>330-390</td>
<td>220-1090 ± 3%</td>
</tr>
<tr>
<td>Stag. temp. (K)</td>
<td>900-1200</td>
<td>300 ± 3%</td>
</tr>
<tr>
<td>Mach number³</td>
<td>2.07</td>
<td>1.7</td>
</tr>
<tr>
<td>Static press.³ (kPa)</td>
<td>39-47</td>
<td>50-220</td>
</tr>
<tr>
<td>Static temp.³ (K)</td>
<td>480-640</td>
<td>190 ± 5%</td>
</tr>
<tr>
<td>Equivalence ratio</td>
<td>0-0.35</td>
<td>± 5%</td>
</tr>
</tbody>
</table>

³ Property at nozzle exit determined using nozzle area ratio and assuming isentropic flow

A schematic and photograph of the existing scramjet combustor at the University of Virginia that was used for 3D PIV measurements as part of this research effort is presented in Fig. 2. The assembly is a "direct-connect" type, with a flow path consisting of a two dimensional Mach 2 nozzle, a constant area rectangular isolator and a rectangular combustion duct. One of the walls of the scramjet combustor includes an unswept 10° compression ramp fuel injector. Hydrogen fuel is introduced from the base of the ramp via a Mach 1.7 conical nozzle. Compression ramps are a popular choice for scramjet combustor fuel injectors because the counter rotating vortices of the ramp wake accelerate fuel-air mixing. Using the normal height of the ramp (H=6.4 mm) to normalize linear dimensions, the isolator and combustion duct inlet dimensions are 4H×6H. The total length of the isolator is 40H. Flow exits the combustor to atmosphere at 58H downstream of the ramp. The walls of the isolator and combustor are instrumented with low frequency pressure taps, high frequency pressure gauges and thermocouples. Optical access is available through windows on three walls of the combustor section. Typical hydrogen fuelling conditions are listed in Table 1. The fuel is ignited by a hydrogen-oxygen detonation driven ignition system. Combustion is self-sustaining following ignition.

Figure 2: University of Virginia scramjet combustor geometry
   a) schematic, and b) photograph of installed hardware
Figure 3 schematically shows the 3D PIV process as applied to the scramjet combustor test section at the University of Virginia. PIV is based on the simple idea that the velocity of an object can be determined by knowing two positions of the object and the time required for the object to move between these two locations. PIV uses small particles added to the flow as the tracer “objects” and two temporally spaced images of these particles are obtained. In the present application, 0.3µm alumina particles were used. Using computer algorithms, the velocity of the particles can be determined from particle positions as depicted in the two particle images. The top portion of Figure 3 shows two digital cameras positioned to view the flow inside the test section (isolator section is not pictured) using the test section side windows for optical access. Note that the cameras are angled and set apart in order to view the flow from two different directions. The field of view seen by each camera is broken into small interrogation sub-regions (center of the figure) and correlation algorithms are applied in order to obtain velocity vectors as viewed by each camera. Once the 2D velocity vectors have been generated, those in matching physical positions in the flow are combined through a predetermined mapping function into 3D vectors in real space – shown in the bottom of the figure. The mapping function is determined via a calibration procedure.

Results
Efforts to apply the SPIV technique to the supersonic combustion facility at the University of Virginia have been conducted and good initial results have recently been obtained. Figure 4 schematically depicts velocity measurement planes downstream of the ramp fuel injector. The data presented here was obtained at the X/H = 10 location downstream of the ramp fuel injector. Measurements at locations of 8H and 12H, respectively, will be conducted in the near future along with measurements at the tunnel exit plane. Figure 5 presents some instantaneous and time-averaged velocity field measurements using the SPIV configuration adopted. These measurements were obtained for mixing of hydrogen and air at an approximate equivalence ratio of $\phi = 0.25$ without combustion, i.e. measurements obtained prior to igniting the flow. Figure 5a depicts a 3D view of the time-averaged velocity field at 10H downstream of the fuel injector and the 3D vectors clearly show the dominating axial velocity component of this flow of approximately 920 m/sec. This time-averaged vector field was obtained by averaging 708 instantaneous velocity field results. A more interesting picture of the flow results when examining the in-plane velocity vectors of the time-averaged vector field. Figure 5b is a 2D view of the cross-plane of the time-averaged flowfield. The scale indicates the magnitude of the 3D velocity vector and the scale to the right of the cross-plane view applies to both the 3D and cross-plane views of the time-average velocity field. The predominant features in this cross-plane are the velocity vectors representing the flow of the two counter-rotating vortices that are induced by the ramp fuel injector. Careful examination of the 3D velocity vector picture in Figure 5a also shows the influence of the two counter-rotating vortices, but this is somewhat obscured by the large axial component. A purely axial flow would result in 3D vectors that point directly downstream. However, here the presence of the in-plane motion created by the ramp-induced vortices causes the 3D vectors to tilt away from the downstream directions to varying degrees, depending on the in-plane velocity magnitude at different locations within the vortices. Figure 5c depicts a cross-plane view of one of the 708 instantaneous velocity field results that make up the averaged velocity field of Figure 5a and 5b. Each of the instantaneous velocity field measurements may not contain velocity data for the entire flow field because areas of low seed particle density do not yield reliable velocity measurements. However, when averaging a set of instantaneous velocity measurements, the resulting velocity field contains vectors throughout the seeded fuel plume area. Furthermore, even though the instantaneous field in Figure 5c contains areas lacking velocity vectors, this instantaneous measurement clearly shows the presence of the two counter-rotating vortices. For the results presented here, only the fuel stream was seeded. Figure 5d presents turbulence intensity information for the data of Figure 5a. Turbulence intensity in the fuel-air mixing plume is on the order of 17%. Figure 6 presents views of velocity fields similar to those represented in Figure 5, but the vector fields in Figure 6 were obtained for fuel/air combustion. Figure 6a and 6b show a 3D and cross-plane view, respectively, of the time-averaged velocity field during combustion for an approximate equivalence ratio of $\phi = 0.25$. In this situation, the average measured velocity is lower than in the fuel/air mixing case without combustion and that result qualitatively matches the change in velocity due to heat addition that is predicted by theory. Note also that the area containing velocity vectors is larger than that of the non-combusting, mixing case indicating a larger fuel plume during combustion. This result matches fuel plume images previously obtained for this scramjet combustor which show a larger fuel plume during combustion than during fuel/air mixing without combustion. In Figure 6, the presence of the two counter-rotating vortices can again be seen, however the strength of the two vortices seems to be diminished during this fuel/air combustion case. Further comparison of Figures 5d and 6d yields differences in the turbulence intensity distribution induced by the heat.
Figure 3: Schematic of 3D PIV technique in dual-mode scramjet combustor
Figure 4: Measurement planes for 3D PIV velocity measurement in DMSJ combustor

a.) 3D view of time-averaged velocity
b.) Cross-plane of time-averaged velocity
c.) Instantaneous velocity field measurement
d.) Turbulence Intensity

Figure 5: Measurements of the velocity field inside the test section of the DMSJ combustor during fuel/air mixing without combustion
release of combustion. With combustion, turbulence intensity levels increased to near 25%.

These results show that the application of SPIV to the supersonic combustion facility at the University of Virginia has been successfully developed. These measurements, and additional experimental data obtained in the near future, will be useful for furthering the understanding of the complex velocity field inside a scramjet combustor.

**Future work**
In the immediate future, velocity data at 8H and 12H will be conducted so that the evolution of the ramp-induced vortices as they propagated downstream can be investigated. Next, SPIV will be used to quantify flow properties at a single measurement plane just downstream of the extender section of the tunnel - that is, at the tunnel exit plane. By comparing results obtained at measurement locations of 8H and 12H in the combustor section, the evolution of the ramp-induced vortices near the ramp fuel injector can be examined. Then by comparison to measurements obtained at the tunnel exit, the evolution of the vortices through the extender section and the subsequent shock train can be determined. Lastly, the velocity field as measured at the tunnel exit can be combined with other measurements being conducted concurrently on this

![3D view of time-averaged velocity](image1.png)  
![Cross-plane of time-averaged velocity field](image2.png)  
![Instantaneous velocity field measurement](image3.png)  
![Turbulence Intensity](image4.png)

**Figure 6: Measurements of the velocity field inside the test section during combustion**
tunnel in order to determine the combustion efficiency of this scramjet combustor.

Additional work that is beyond the scope of the current project could also be completed in the future to give additional velocity information in the combustor section just downstream of the ramp fuel injector and also just upstream of the ramp. The sidewalls of the test section could be redesigned to accommodate new side windows that allow for optical access at measurement planes of X/H = 2, 4 and 6. Velocity measurements at a final measurement location upstream of the point of fuel injection would be useful for quantification of velocity field and free-stream turbulence upstream boundary conditions. For all measurement planes, the obtained velocity fields would be used to determine turbulence intensity and vorticity and would likely be compared to any available CFD efforts for predictive-tool validation.

**Conclusion**

Basic characteristics of the SPIV technique as applied to the scramjet combustor at the University of Virginia were presented along with velocity field and turbulence intensity measurements that have been obtained using the scramjet combustor. The influence of the two counter-rotating vortices induced by the unswept ramp fuel injector can clearly be seen in both the case of fuel-air mixing without combustion and in the case of fuel-air combustion. Future work will use current and future measurements to quantify velocity, turbulence intensity, vorticity and the effects of heat release on flow field characteristics. These efforts will help to gain a better understanding of the complicated three-dimensional flow field inside a scramjet during fuel/air combustion. Furthermore, these results will be used to help validate Computational Fluid Dynamics simulations being developed at NASA Glenn Research Center and elsewhere.

**References**