Abstract:
The Aerospace Research Laboratory at the University of Virginia currently uses Particle Image Velocimetry (PIV) to measure the velocity fields of flow through a Mach 2 Scramjet Test Section. PIV is the method of tracking seed particles as they are carried through the flow, and using their velocities to create a velocity field. This method is limited by seed particles coating the windows, known as window fouling, making seed particle tracking within the flow impossible. This paper will discuss a potential improvement to the PIV system that will attempt to reduce the effect of window fouling. The potential improvement will involve the use of a molecular iodine absorption filter, as in Planar Doppler Velocimetry (PDV), to separate out the signals of moving particles from those with little to no velocity coating the window. This paper will discuss the feasibility of this potential improvement, and describe how the improvements may be implemented.

Introduction
Dual-Mode Scramjet (DMSJ) engines are designed to operate efficiently at a wide range of velocities by combining both ramjet and scramjet technology. At lower velocities of Mach 3 to 5, a DMSJ engine will operate as a ramjet. In this mode the engine takes in the free stream supersonic flow and compresses it to subsonic speeds. This compressed air is then sped up to supersonic speeds via a combustion reaction and then exhausted through an exit nozzle to produce thrust. At higher velocities above Mach 5, a DMSJ engine operates as a scramjet, which is identical to a ramjet except that the flow remains supersonic throughout its entirety, even after compression\(^1\). This switch occurs because at higher velocities it becomes increasingly inefficient to create a normal shock wave system to bring the velocity below Mach 1\(^2\).

One advantage of a DMSJ engine is that the incoming flow itself is used to supply the oxygen for combustion. Thus it is not necessary to carry oxygen fuel tanks, saving both money and payload. DMSJ engines are also preferable to conventional engines at high speeds because of the simplicity of the system\(^1\). Unlike many conventional methods of producing thrust that contain many moving parts, DMSJ engines have almost no moving parts\(^2\). This simple system is much easier to operate at high speeds than complicated systems such as a turbine or piston based engine. For these reasons, DMSJ engines are of interest as a mode of thrust production for long distance, high velocity flight and for two stage access to orbit\(^1\).

Figure 1 is a good depiction of a DMSJ engine. The flow through a DMSJ first goes through an inlet, which is only open when the vehicle is above the appropriate speed. After this intake, the flow goes through an isolator section. This section is of constant area, and is meant to eliminate combustor-inlet interactions while also compressing the flow. In ramjet mode this is where the flow would be compressed to a subsonic velocity, but in scramjet mode the flow just compresses to a lower supersonic velocity. In both modes, the compressed flow then goes through the combustor stage. At this stage, hydrogen or hydrocarbon fuel is injected into the flow via a fuel ramp injector or a cavity flame-holder, in an effort to mix the fuel. The fuel-air mixture is combusted to supersonic velocities, re-crossing the sonic barrier in a ramjet, so that when it exits the nozzle it produces thrust for the vehicle.\(^1\)
While scramjets are a promising future technology, there is still much to understand about the flow patterns that take place within a scramjet engine. The Aerospace Research Laboratory (ARL) at the University of Virginia has been conducting flow field measurements on a Mach 2 Scramjet wind tunnel to improve the current knowledge of these flow patterns. The ARL uses Particle Image Velocimetry (PIV), a tracking technique, to measure the velocity field of the flow. Results from this research are used to verify computer models of flow through a scramjet, through which the flow patterns can be better understood.

There is a difficulty that occurs when attempting to use PIV on a flow with such a high speed and temperature. Seed particles that are necessary for PIV begin to coat the windows of the test section, preventing data from being captured by the PIV apparatus. This problem is termed window fouling. This paper will investigate a potential solution to the issue of window fouling that involves the use of molecular filters to reduce the signal strength produced by seed particles coating the windows.

**Background**

**Facilities**

The Supersonic Combustion Facility at the University of Virginia consists of a supersonic wind tunnel that is both electrically heated and contaminate free. The tunnel is capable of creating flows at speeds near Mach 5. The tunnel is unique in that it can provide continuous flow for indefinite periods of time. This causes the limiting factor of PIV run time to be the window fouling that occurs during experiments.

There is a direct-connect scramjet combustor installed atop the wind tunnel, allowing the tunnel to simulate flight using a scramjet engine. The scramjet combustor consists of a Mach 2 nozzle, a rectangular isolator, and a combustor. The ability to inject the flow with particles necessary for PIV is available in both a free stream and the fuel injector. Ref. 3 through 8 should be viewed for a more complete description of the facilities.

**Particle Image Velocimetry:**

Particle Image Velocimetry is a method used to characterize the velocity field of a specified flow in terms of the movement of particles injected into the flow. This is done at the University of Virginia on a Mach 2 Scramjet test section by injecting laser-illuminable particles into the flow field, and capturing the movement of those particles. Two laser beam pulses are fed nearly simultaneously through a series of optical instruments in order to transform the beams into planes of laser. These laser planes are aimed to coincide with the desired plane in the flow field to illuminate the injected particles residing in that plane. For two-dimensional PIV, a high speed camera is used to capture the two near simultaneous images illuminated by the pulses. The data from these images are put into correlation software that will then output the two-dimensional velocity field of the flow. For three-dimensional PIV, also known as Stereoscopic Particle Image Velocimetry (SPIV), two high speed cameras positioned at angles to the laser sheet planes capture the illuminated images and correlation software will output the three-dimensional velocity field of the flow.
A simple setup of PIV is shown in Figure 2. As described, the flow is injected with particles, which are labeled in Figure 2 as seeding. A laser sheet illuminates the seeded particles, and the camera takes the image of the particles at various times. In Figure 2, however, there is only one camera and it is aimed directly perpendicular to the flow direction. In this case, only 2 dimensions of the velocity field can be determined. The velocity component towards and away from the camera is undeterminable. Two cameras placed at angles to the laser sheet plane allow for a calculation of velocity in all three spatial dimensions. For a more in depth description of how PIV and SPIV are conducted, see Refs. 3, 8, 9, and 10.

One of the major problems with using PIV in the Mach 2 Scramjet test section is window fouling. Window fouling occurs when the seed particles begin to stick to windows of the test section, covering the windows with a fog that obstructs the view of the cameras. This problem gradually gets worse over the course of a run, to the point that meaningful data can no longer be collected. Reducing this experimental problem would allow for previously unattainable data to be collected, furthering the current understanding of flow through a scramjet.

### Planar Doppler Velocimetry

Planar Doppler Velocimetry (PDV) is another method of flow velocimetry. Also known as Doppler Global Velocimetry, Filtered Planar Velocimetry, Absorption Filter-Planar Doppler Velocimetry, and Filtered Rayleigh Scattering, PDV utilizes the Doppler Effect to determine the velocity field of the flow. The technique relies on measuring the Doppler shift of laser light that scatters off of moving particles in the flow. Unlike PIV, the particles that scatter the light can in some cases be part of the flow itself, though in other cases seed particles may be required. When the light hits these particles, it undergoes a Doppler shift in frequency depending on the particles velocity and relative angles of the laser sheet and camera viewpoint. The change in frequency can be related to the flow velocity vector by the equation:

\[
\Delta f_D = \frac{(k_x-k_0)\cdot V}{\lambda}
\]

where $\Delta f_D$ is the change in frequency of the light, $k_x$ is the unit vector going toward the direction from which the viewing area is being viewed, $k_0$ is the unit vector going in the direction in which the laser light is initially traveling, $V$ is the velocity vector of that point in the flow field, and $\lambda$ is the initial wavelength of the laser light. The two unit vectors and the initial wavelength of the laser light can be chosen, so if the change in frequency at a point in the flow can be measured, the velocity vector at that point in the flow can be calculated.

To obtain a measurement for $\Delta f_D$, molecular filter cells are used. These cells are filled with a gas that has a known absorption spectrum. In the case of PDV, diatomic iodine is a common choice of gas. As light passes through the cell, certain frequencies of light are absorbed more than others. Thus the intensity of certain frequencies of light diminishes more than others as light travels through the filter cell. Absorption spectra are characterized by small thin spikes in absorption levels over small frequency ranges and relatively long frequency ranges of high transmission levels. Figure 3 shows...
The absorption spectrum of a gas will change depending on its temperature and pressure, so the cell must be monitored and controlled to maintain the desired properties. The temperature and pressure chosen can be used to tune filter cell to maximize sensitivity for the expected frequency changes. A condition is chosen so that the initial laser frequency lies on one of the extreme slopes of an absorption peak. This allows a distinction between an increase in frequency and a decrease in frequency, as one will increase transmission and one will decrease transmission, depending on which side of the absorption spike the initial frequency lies.

The molecular filter is placed in front of a CCD camera much like the ones used in PIV. The scattered laser light is sent both through the filter to this camera, and to a reference camera that is not filtered. By comparing the relative intensities of light in each pixel, the transmission level of light at that location can be determined, which corresponds to one unique frequency within a small frequency range. Using this frequency and the initial laser light frequency, the Doppler shift $\Delta f_0$ can be determined, and from that the velocity vector $\mathbf{V}$ can be calculated from equation (1) for each pixel. With this information, a velocity field can be formed.

**Proposed Solution**

The potential solution that this paper will investigate is the use of molecular filters to reduce the problem of window fouling in PIV. The basic premise is to cause the window fouling particles, which have little to no velocity, to produce lower signal intensity when they are imaged by filtered cameras than they would normally produce. Though testing would be needed, it is possible that lowering this signal intensity would reduce the background signal caused by window fouling.

The goal of this solution is to lower the signal intensity of window fouling particles. It is not necessary to use the filters to actually measure the Doppler shift or velocity of the particles as in PDV, as the PIV system is already set up to do this. This makes the filter setup simpler than in PDV in that a reference camera is not required because measuring the relative transmission levels will not be important. A molecular filter placed directly in front of the PIV cameras should be able to achieve the goal. The ability of the molecular filter to perform in such a way as to decrease the signal of window fouling particles is dependent on choosing a proper absorption spectrum, which can be done by selecting the proper filter gas and cell conditions.
Gas Selection

A common gas selection for the purposes of PDV molecular filters is diatomic iodine gas\textsuperscript{14,15,16}. This is due to its satisfying of four main criteria: molecular weight, isolation of absorption lines, absorption line strength, and wavelength of absorption lines\textsuperscript{18}.

It is desirable to maximize filter sensitivity to changes in flow velocity, which can be accomplished by maximizing the slope of the absorption lines. The slope of the absorption lines is shown to be inversely proportional to the thermal linewidth in the cell\textsuperscript{19}, which can be calculated by:

\[
\delta = \frac{1}{4} \sqrt{\frac{2kT}{M}} \quad (2)
\]

where \(\delta\) is the thermal linewidth, \(k\) is the Boltzmann constant, \(T\) is the gas temperature, and \(M\) is the molecular weight of the gas. Minimizing the thermal linewidth maximizes the slope of the absorption lines, so a high Molecular weight is preferred\textsuperscript{18}. With an atomic number of 52, diatomic iodine gas is a relatively heavy gas.

Isolation of absorption lines refers to the frequency separation between absorption lines. A larger separation prevents ambiguity in transmission levels because frequencies with identical transmission values are so far apart that they will not likely appear via a Doppler shift. Absorption line strength is the extent to which a gas absorbs light within its absorption line frequencies. In Figure 3, the longer lines are said to be stronger absorption lines. A stronger absorption line allows the utilization of the full dynamic range of the camera, maximizing sensitivity. Iodine gas satisfies both of these criteria.

The wavelengths of absorption lines of diatomic iodine gas lie in the desired range for most PDV experiments, which use lasers with wavelengths in the range of 400-600 nm. Such lasers lie in the visible light scale, in which iodine has many absorption lines that can be exploited to filter light. Because the laser currently used in PIV at the ARL is similar in wavelength (532 nm) to lasers commonly used in PDV, iodine gas has acceptable wavelengths of absorption lines for this purpose\textsuperscript{18}.

Spectrum Determination

The diatomic iodine gas must be tuned to a specific absorption spectrum by choosing the conditions of the filter cell. The goal is to have the transmission of light scattering off of slow moving particles be as low as possible, and the transmission of light scattering off of particles in the actual flow be as high as possible. Light that scatters off of still particles will not acquire any change in frequency from the Doppler shift according to equation (1), as the velocity vector \(\mathbf{V}\) in that case is a zero vector. Thus the frequency of light scattering off of window fouling particles will be at or near that of the initial laser frequency. This indicates that the iodine absorption spectrum should be tuned so that the peak of a strong absorption line corresponds with the initial frequency of the laser light.

The high speed flow particles will cause light scattering off of them to acquire a relatively large Doppler shift in accordance with equation (1). Depending on the relative angles of the cameras and the laser sheet to the flow field, this frequency shift could be either an increase or a decrease from the initial laser frequency. The requirement that light scattering off of high velocity particles in the flow has a high transmission level indicates that the iodine absorption spectrum should be tuned so that a region of relatively constant and low absorption level coincides with the Doppler shift range expected from the flow. Figure 4 shows the layout of the desired absorption spectrum with respect to the initial laser frequency and the expected Doppler shifted frequencies.

With the goals above stated, a set of filter cell conditions must be determined that create such an absorption spectrum. The first goal is easily satisfied by finding a set of conditions that causes an absorption peak to occur at the initial laser wavelength of 532 nm. Finding a spectrum that satisfies the second goal as well is highly dependent on the particular experiment. Different experiments can have different values for \(\mathbf{V}\), \(k_e\), and \(k_0\) with regards to equation (1), which will result in different frequency shifts. The location of regions of relatively constant, low absorption depend on what frequency shifts are expected. Therefore the chosen absorption spectrum will be different depending on the experiment.
An example calculation of expected frequency shift will be done for a single camera of a simple setup of this molecular filter aided Particle Image Velocimetry. The laser used for this example will have a wavelength identical to the laser currently used at the ARL, with a wavelength of 532 nm. To determine the unit vectors $k_s$ and $k_0$, a coordinate system must be established. Figure 5 shows the chosen coordinate system with reference to the test section. The $x$-axis is the primary direction of the flow, that is, parallel to all four walls of the test section and pointed vertically upwards. The $y$-axis will be pointed perpendicular to the longer walls and parallel to the shorter walls of the test section. The $z$-axis will be perpendicular to the shorter walls and parallel to the longer walls of the test section, and its direction can be found by using the right hand rule with the $x$-axis and $y$-axis.

Under this coordinate system, the laser sheet will propagate along either the $y$-axis or the $z$-axis, depending on the experiment. For this example, let it propagate along the $y$-axis. Thus the unit vector $k_0$ will have a value of $[0,1,0]$. The camera will be placed at an angle to the laser sheet of between 0 and 90 degrees above the $y$-$z$ plane. For this example the angle is chosen to be 45 degrees, and the camera is said to lie on the $y$-axis, but on the positive $y$-axis side of the test section. Thus the unit vector $k_s$ will have a value of $[.707, .707, 0]$.

To make this example applicable to PIV at the ARL, the velocity vector $V$ will have a magnitude of very near to Mach 2 at 1000 m/s. For this simple example, the flow will be considered to be entirely along the positive $x$-axis. Thus the velocity vector $V$ will have a value of $[1000, 0, 0]$ m/s.

Using these values for $\lambda$, $k_0$, $k_s$, and $V$, the expected shift in frequency can be calculated. The expected frequency shift is about positive 1.33 GHz, that is, the shifted frequency will be 1.33 GHz larger than the initial laser frequency. Considering that the initial laser has a wavelength of 532 nm, which corresponds to a frequency of 563.52 THz, a shift of 1.33 GHz is not a relatively large shift in frequency. It corresponds to a wavelength shift of only negative 1.255 pm, or since absorption spectrum are often presented in terms of wave number in units of cm$^{-1}$, a wave number shift of only positive .0443 cm$^{-1}$.

Thus in this case the desired absorption spectrum must have an absorption peak at the initial
wavelength of 532 nm, and a relatively low absorption level at wavelengths just slightly below 532 nm. This small differential between un-shifted light and shifted light promotes the use of molecular filters, as a thin, isolated absorption peak located at a wavelength of 532 nm will be able to satisfy the two original goals. Since the typical linewidth as estimated by Forkey et al is 1 GHz for iodine absorption lines\textsuperscript{21}, the absorption line should be thin enough to discern the difference in light frequency of 1.33 GHz.

This example calculation made many oversimplifying assumptions, and in conducting a real Doppler shift calculation it is recommended that the literature on PDV and molecular filters be consulted. For example, the assumption that velocity flow is entirely in the x-direction will not be accurate for scramjet flow. Velocity measurements using SPIV have shown that while time-averaged velocities are simple and fairly consistent, instantaneous velocities are complicated and sporadic\textsuperscript{3}. The best course of action is to estimate a range of expected instantaneous velocity vectors, and determine the possible Doppler shifts in frequency for those expected velocity vectors.

**Cell Conditions**

With a desired absorption spectrum known, the proper cell conditions to achieve this spectrum must be found. There are four main variables responsible for the absorption spectrum of a molecular filter cell\textsuperscript{18}:

1) The gas contained within the cell
2) The length of the cell
3) The temperature of the cell
4) The pressure of the cell

Diatomic iodine gas has already been designated as a good choice for this purpose, so only the other three variables will determine the absorption spectrum. Forkey et al developed a computer model designed to accurately predict the absorption spectrum of diatomic iodine filter cells for light near a wavelength of 532 nm\textsuperscript{21}. Using this computer model, the conditions required to tune a molecular iodine filter cell to any possible absorption spectrum can be determined. Requesting the computer codes developed in Ref. 21 is be advised in order to properly tune iodine filter cells for this purpose. While the computer model from Ref. 21 is useful in getting an accurate estimate of required cell conditions, testing and calibration is required to ensure that the absorption spectrum is as expected.

**Conclusion**

Particle Image Velocimetry is an effective and non-intrusive tracking technique for measuring the velocity field of high speed flows. A major problem is that the seeding particles that are necessary to track the flow will eventually coat the test section windows with a fog, obstructing the view of the PIV cameras. This obstruction is responsible for preventing lengthy PIV experiments in the Supersonic Combustion Facility at the University of Virginia.

The problem of window fouling in PIV may be diminished by utilizing the molecular iodine filter cells that are used in PDV. By placing the cells in front of the PIV cameras, the cells can be used to reduce what is essentially background noise produced by window fouling particles. If the expected velocity of the flow in question can be guessed to a sufficiently accurate degree, then an absorption spectrum can be imagined that will reduce the signal of non-moving particles, such as those causing window fouling. Through the use of a computer model\textsuperscript{21}, the cell conditions necessary to create that absorption spectrum can be found, and the cell can be set to those conditions.

The solution has not yet been tested or verified in an experimental manner. Before attempts to use this possible solution on PIV, it is recommended that testing be done to show that molecular iodine filters can reduce the background noise of window fouling particles, and that the inflow particles will be more easily imaged as a result. If this proposed solution does have an effect, it will not be to completely eliminate the problem of window fouling. It would only increase the allowable time for data collection before window fouling prevents it completely.

**Future Work**

This paper has demonstrated the feasibility of using a molecular filter cell to reduce window fouling effects. It is recommended that steps be taken to begin experimental testing of the proposed solution, in hopes of implementing molecular filters into PIV work at the Aerospace Research Laboratory at the University of Virginia.

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