Abstract
In order to make scramjets, supersonic combustion ramjets, more widely used, the University of Virginia is studying the ingress path of the fuel with the supersonic airstream in a scramjet combustor. However, during particle image velocimetry (PIV) testing, seeded particles get stuck to the window, obstructing the camera view. It is hypothesized that the window and particles become triboelectrically charged, and are electrically attracted to one another. By applying and grounding a conductive film to the window, the charge is dispersed when it builds up, thus discouraging particles from sticking to the window. To test this hypothesis, a slide with indium tin oxide (a conductive coating) was attached to a window. After running the wind tunnel with this test slide and a high particle concentration, it was observed that the particles did not stick to the slide with the ITO, but there were particles stuck to a blank window. However, the results are inconclusive because the pattern of particles deposited on the uncoated slide was not consistent across the area of the slide. This does not discount the hypothesis of triboelectric charging and further experiments should be done to decide if conductive films will improve results of PIV testing.

Nomenclature

ARL = Aerospace Research Lab
ITO = Indium Tin Oxide
PIV = Particle Image Velocimetry

Introduction
The current age of transportation is pushing the barriers of the new frontier of air and space. This physical barrier is Mach 1, a point in flight that can allow people to get places faster, both around our planet and out of our atmosphere. Currently this technology is limited to military pilots, but with more fuel injection research could be commercially accessible. Scramjets are air-breathing jet engines that keep air speeds supersonic when fuel is inserted and then combusted. By using the oxygen in the air and fuel particles as the oxidizer and propellant, respectively, launch mass and cost are reduced, which increases efficiency. The ability for a scramjet to take off and land as a plane also increases the safety of travel. Research at the Aerospace Research Lab (ARL) at the University of Virginia is designed to study the path of the fuel as it enters the supersonic airspeed within the tunnel. This will result in a better understanding of the fuel and air mixing to better understand the combustion process. However, when particle image velocimetry (PIV) particles are seeded into the wind tunnel for testing, they are getting stuck to the window and obstruct the view to test. It is hypothesized that these particles are triboelectrically charged to be attracted to the window; when particles are seeded, an extra force acts on them to draw them to the window. This would also affect the discrepancy of the path of the particles because of a force that is not experienced within a typical scramjet.

This paper begins with details of the background to the problem of particle adhesion to the wind tunnel windows during PIV testing by describing the current test setup and the PIV procedure. It then goes on to give context to the hypothesis that the particles and windows are triboelectrically charged and that indium tin oxide (ITO) would be an
appropriate solution to the charging. The experimental plan is described and results are recorded. Finally, the results are discussed to draw conclusions between what was expected and what occurred in testing. The lack of correlation between the predicted and resulting results indicated the inconclusiveness and describe further testing that should be done to further support the use of ITO.

**Background**

Within a scramjet, the air is taken in through a nozzle at the hypersonic speeds at which it is flying. Fuel particles are then injected through the fuel injector, mixed with the air, and then the two are combusted downstream to continue to propel the scramjet forward. Figure 1 shows the diagram of the dual-mode scramjet combustor and Figure 2 is the diagram of the overall wind tunnel. Since oxygen from the air is used instead of liquid oxygen, the scramjet has to carry less oxidizer, making it much more weight and cost efficient than a conventional rocket. However, it adds an uncertainty of how the air and fuel particles will mix. For example, vortices form around the injection site as the fuel is injected. By learning more about these uncertainties, scramjets be designed safer and more efficiently.

![Figure 1. Dual-mode scramjet combustor. Fuel particles are injected into the supersonic airflow in the nozzle and then both are combusted downstream at supersonic speeds.](image1)

In order to study the flow path of the fuel particles, U.Va. uses PIV extensively. PIV begins with the insertion of Silicon (IV) Oxide or Titanium (IV) Oxide into the supersonic airflow of the vertical wind tunnel. A laser is flashed and a picture is taken of the particles through two observatory windows in the tunnel. A few microseconds later, the laser is flashed again and another picture is taken. The change in distribution of particles is observed between the two pictures to calculate particle velocity vectors and flow paths can be observed. However, if the observation window gets clouded with particles during testing, pictures do not clearly show where the particles are within the flow.

**UVa Supersonic Combustion Facility**

![Figure 2. Vertical hypersonic wind tunnel. The UVA Supersonic Combustion Facility has its vertical hypersonic wind tunnel connected to the dual-mode scramjet combustor.](image2)

Triboelectric charging is the electric charging of two materials when they come in contact with one another because of friction. Because quartz is more electropositive, it is more likely to lose an electron; conversely, silicon dioxide and titanium dioxide are more electronegative, which makes them more prone to take electrons from glass. Thus, the quartz windows become positively charged while the seeded particles, SiO$_2$ and TiO$_2$, become negatively charged. This electrical difference creates an attraction between the window and seeded particles which causes the particles to adhere and coat the window during testing. Therefore, a photo cannot be taken because the field of vision is obscured by coated particles. Also, this electrical force
could have an extra effect on the study of how the particles move when inserted into the airflow.\(^4\)

Because the wind tunnel is often run hot, the window and window frame shrink and expand with temperature changes. Therefore, the wind tunnel is designed with a slight gap between the window and frame in order to assuage the change in size. However, this gap in the window also prevents the window from being grounded. If a charge were to build up on the window, it would not be dispelled during the testing. The charged particles then deposit themselves on the quartz window.

By making the glass window more conductive and grounding it, the charge can be dispelled during testing easily and continuously in order to keep experiments going within the wind tunnel. ITO is a transparent conductive oxide with a high melting point that can be applied in very thin layers over a surface. By applying a thin film of ITO on the insides of the windows and grounding the coating, charge buildup on the windows can be dispelled during use of the wind tunnel. ITO film has a slight yellow tint, but it is transparent in the visible spectrum, allowing pictures to be taken through it.\(^5\) Also, the coating has a melting point of about 1900 K, which will make it applicable for use during hot tests within the wind tunnel, which runs at about 1200 K.

**Experimental Testing**

**Testing**

In order to test whether a thin film of ITO will dissuade particles from sticking to the windows, a cold run of the tunnel was done with samples coated in ITO. Two quartz slides were purchased, one with a 2000 Å coating of ITO that has a resistivity of 10-20 Ω and one without the ITO coating.\(^6\) Both were attached to the downstream portion of a wind tunnel window with two-part epoxy. This placement was chosen because when looking at a window that went through PIV testing, two broad bands of particles built up across the window in distinct spots. Each test slide was placed on the window where one of these bands was predicted to appear. A strip of conductive tape was attached to the bottom of both plates and around the sides of the window. When the window was installed into the frame and finally the wind tunnel, the ends of the conductive tape were fed around the sides of the frame and attached to the wind tunnel in order to ground the ITO coating. It was confirmed that there was an electrical signal from the ITO coating to the edge of the conductive tape. *Figure 3* shows the final setup of the slides installed in the wind tunnel before testing.

![Figure 3. Test Setup with test slides. The top slide has a coating of ITO and the bottom slide is uncoated. Both are grounded by the copper tape that wraps around the window frame and grounds itself to the wind tunnel.](image)

The wind tunnel was set up to do a cold run with a high concentration of seeded particles. After about 15 minutes of running the tunnel up to speed, the air flow was recorded to be 14.4±.2°C and the stagnation pressure was 21.8±0.1 psig. This air pressure corresponds to an air speed of 525 meters per second. The seeder was started and set to about 35 psi. The airflow ran at these conditions for 12 minutes and then increased to 38 psi for another 20 minutes. From observations, it was seen that there was a film
of particles on the control window, indicating that the wind tunnel and seeder worked correctly to replicate the problems seen on the windows during other wind tunnel tests.

Observations

After turning off the airflow and seeder, the windows were carefully extracted from the wind tunnel and window frames. It was concluded that both windows were well coated with particles, as seen in Figure 4a and Figure 4b, assuring that the current windows were susceptible to attracting particles, causing buildup during testing. However, there were not typical patterns coating the windows as there are during hot testing. On the control window, there was just a general film of particles and no visible sign of the shock bands that show up downstream, across from where the slides were placed. When looking at the coated and uncoated slides, it can be seen that there are some particles built up on the uncoated window, but there are no particles visible on the ITO coated slide. Figure 4c shows the ITO coated (left) and uncoated (right) slides after testing.

The particle buildup on the uncoated slide was abnormal to how it is generally built up. At that specific location on the window, a hot test in the wind tunnel will cause a general film of particles with a noticeably thick band of particles running through it. In this test, a film of particles only occurred on the third of the slide furthest downstream of the window. These observations are taken with the unaided eye and camera. More analysis with a microscope is needed to analyze microscopic particle depositing.

Discussion

Although the ITO coated slide was free of particles and the uncoated slide did have a portion covered with film, the results of this test are inconclusive. It is a positive sign that the slides turned out as they did, but more factors than just conductivity could have played a role in the end results. Since the coated windows come out of a normal PIV run with two thick bands at the end of the window, it was expected that these bands would result in this run too. However, the only coating seen between both of the slides was on
the last third of the uncoated slide. This different depositing pattern of the uncoated slide indicates that something has changed in the air flow over the window of the wind tunnel. The lack of particles on the side of the slide closest to the conductive tape could indicate that grounding the slide helps to a certain point. However, it could also indicate that when particles run into the change in elevation of the window, the flow path of the air is deflected away from the window. This would also move the particles away from the window, and if the particles do not fully track the flow (due to their inertia), they may only return to the slide near its downstream end. This deduction would then have an effect on the pattern of the particles depositing on the second slide. The placement of two elevated slides along the window of the wind tunnel could create abnormal flow within the tunnel, which changes the patterns of the depositing of particles along the window.

Furthermore, the control window did not show any signs of thick bands of particle deposits at the downstream end, often indicative of a hot test. This could be caused from either a change in the flow path and speeds because of the elevated slides on the window or a difference in particle depositing between hot and cold runs.

Therefore, more testing needs to be done in order to analyze the effect of using an ITO coating on the inside of the windows of the wind tunnel during PIV testing. Further experiments are recommended as follows:
-- Examine the coated and uncoated slides from the original experiment under an optical microscope and use counting methods to get a rough quantitative analysis.
-- Run the same experiment procedure, but cut slides in order to put them side by side. Also, build up a small ramp in order to make flow path changes less abrupt.
-- Coat one window in ITO and run the tunnel both cold and hot with the coated and uncoated windows opposing each other. Perform PIV testing at the same time, mapping the flow path of the particles to judge if they act differently next to the ITO coated window verses the uncoated window.

Another explanation for the discrepancy in the predicted and deposited particles is a thick boundary layer over the window. If the boundary layer is thick compared to the height of the quartz slide, the flow velocity near the slide would be small. The particles would thus track the flow well, indicating that the grounding technique of the experiment was successful. One should continue to watch out for a thick boundary layer in further experiments.

Conclusions

A current problem with PIV testing is that particles seeded into the flow path become stuck to the window, fogging up the visible area and preventing good test taking data. It is hypothesized that the particles and window become triboelectrically charged and because the window is not grounded, the charge cannot be dispelled. Therefore, in order to dispel the charge, a combination of a coating of ITO on the window and grounding the window would fix this issue. The testing reported in this paper is inconclusive because too many independent variables were introduced into the experiment. Primarily, it is believed that by introducing a slide that is elevated on the window, the flow path is disturbed. Therefore, an unusual depositing of particles on the uncoated slide results and thus the lack of particle depositing on the ITO coated window cannot be trusted. However, the current results do not discount the triboelectric effect.

The data collected advocates for further experimentation with ITO coatings on the wind tunnel window. The current slides should be further examined, the current experimental plan should be modified to reduce independent variables, and an entire window should be coated in ITO. If the ITO
proves to make a difference, the coating should be implemented in the wind tunnel design.

With further research, ITO coated windows could be the answer to dissuading particles from triboelectrically adhering to the window. This would result in better hypersonic flow path research and the propulsion of aerospace research into the next big thing – scramjets.

Acknowledgements
The author would like to thank Christopher Goyne for being an excellent mentor through this year of research, providing consistent guidance, answers and support. Thanks also to Roger Reynolds, Brian Rice, Robert Rockwell, and all others at the U.Va. ARL that helped in the experiments. Finally, thanks to the Virginia Space Grant Consortium for funding the research over the past year.

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