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Assessment of 3-D Flow Diagnostics for Study of Reaction Jets on Finned Bodies

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An assessment is developed to determine the difficulties associated with combining a recently developed 3-D imaging technique utilizing a custom built pulse-burst laser system and a planar laser-induced fluorescence measurement technique in order to study reaction jets on a supersonic flight vehicle. Three-dimensional images were created of an acetone-seeded jet circumferentially located on a finned model exhausting into a supersonic cross flow. Images taken examine the interaction of the jet and the freestream. The limitations of the current testing apparatus are reported with necessary improvements considered for making accurate 3-D measurements possible for this flow field.

I. Introduction

Advanced 3-D diagnostics is the latest in current technology to fully visualize a flow field. While planar techniques have a purpose, they do not have the capability of capturing the three dimensional effects present in any flow field. A technique has been developed to create 3-D images of a flow field using a pulse-burst laser system [see ref. 1]. A pulsed Nd:YAG laser is focused into thin laser sheets which are swept across an area of seeded flow. Previous experiments used water droplets for seeding the flow field. An image is captured at each plane that is illuminated by the individual pulses as the laser sheets sweep over a volume. Once captured, these images are processed and combined in TecPlot, mostly used for computational fluid dynamics, to create a 3-D flow field. What is amazing about this is that once the plot is created, the volume can be cut in planes perpendicular to the original planes imaged. This allows for a comprehensive technique to fully visualize the flow. The previous experiments were completed using particle scattering with 532 nm light. While the ability to visualize the flow in its entirety is a useful tool, being able to create 3-D measurements of a flow field combined in a similar manner would be ideal. Planar measurements have been completed using laser-induced fluorescence [see ref. 2]. Combining both techniques would allow us to create a three dimensional measurement field. In order to create a working technique, progress has been made looking at reaction jets on finned bodies in a supersonic crossflow. This is both a relevant and complex flow field to test the apparatus.

The need for more effective missile control systems is becoming increasingly essential for defense applications. The threat of intercontinental ballistic missiles (ICBM) and trans-atmospheric flight vehicles places additional requirements on the maneuverability of interceptors, more specifically kinetic energy kill vehicles. In order to successfully take out a threat, these devices must be accurate, because there is no warhead to detonate if the target is missed. To meet these requirements, modern systems often use divert and attitude control system (DACS), a system composed of reaction jets circumferentially located on the vehicle. These devices provide control in

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regions of low dynamic pressure such as the edge of the atmosphere and slow speeds, where traditional control surfaces, such as fins or canards, are largely ineffective. Also, reaction jets provide quick response times compared to these traditional control methods.

Reaction jets are being used on multiple flight vehicles today as a form of dynamic and static stability control. One missile utilizing this technology as a form of control is the terminal high altitude area defense missile (THAAD). This is the first missile with the capability of intercepting an incoming missile both in and out of the atmosphere. Since 2005, THAAD has been able to intercept 29 of 30 incoming test missiles both in and out of the atmosphere. The THAAD program is one example of the capabilities of this technology [3]. However, THAAD does not have any tail fins and relies solely on the propulsion system to produce lift. Many of the problems associated with reaction jets appear in the interaction between the jet flow field and the fins. While fins may increase weight and drag, they are a simple alternative to thrust vectoring for static stability control. A broader application of reaction jets could be obtained through an increase of knowledge on the flow characteristics created by the jet on a finned flight vehicle.

Previous efforts have established the difficulties surrounding the use of reaction jet thrusters on a flight vehicle [see Refs. 4-11]. These difficulties include: wraparound shocks, a lower pressure region aft of the jet, and a counter-rotating vortex pair produced by the jet-in-crossflow interaction. There has been extensive research completed on the complexities of the flow field surrounding a jet in supersonic crossflow on a finned body. First, when a jet is introduced to a supersonic flow field it creates a bow shock. This shock will propagate around the entire finned body. On the jet side, a desired high pressure region, created by the shock, will amplify the force of the jet. However, due to the three-dimensional nature of the shock wrapping around the finned body, high pressure regions will be formed around the rest of the body at the location of the jet. The pressure created on the body opposite of the reaction jet will actually counteract the desired force produced. Therefore, the potential force is actually reduced by this wrap-around shock [9, 10]. Another problem is a relatively low pressure region aft of the shock on the finned body, which results in an increase in moment on the finned body [9, 10]. In some applications, such as pitch control, this large moment actually increases the authority of the reaction jet. However, in applications such as roll control, where a moment is not desired, this low pressure region is detrimental. Control is further complicated through a counter-rotating vortex pair created by the jet [11]. This structure continues downstream and will eventually interact with control surfaces such as fins. In the case of roll control these vortices will cause the downstream fins to counteract the force created by the jets. PIV has been used to visualize these counter rotating vortices as they travel downstream from the jet, and proved the complexity of this flow field [see ref. 11].

The objective of this work is to assess the development of a 3-D measurement technique to further explore the complex dynamics of this flow field. Initial schlieren images were taken to ensure the test apparatus was working properly and confirm the shocks created by the reaction jet in the supersonic crossflow. Several recently developed high-speed 3-D flow visualization techniques were utilized to take pictures along the finned body to create a volumetric 3-D image of the jet fluid. These images allow for visualization of the jet as it develops in the downstream direction. A generic flight vehicle model mounted in a supersonic wind tunnel with acetone-seeded flow on the finned body was developed for the experiments. The following reports the difficulties with creating a volumetric measurement of a flow field. A recording of the work completed to make these advancements in the current technology is used to assess both the limitations of the current system and provide the work necessary to obtain a 3-D measurement of this flow field.

II. Current Experimental Set-up and Facilities

In order to study this flow field a test apparatus was developed to produce the reaction jet flow field. The reaction jet on the finned body is created using high pressure nitrogen seeded with acetone. The acetone is used for particle scattering to capture planar images of the jet fluid field. A wind tunnel model was built to represent a generic finned body, and carry the acetone to the reaction jet. In order to take planar images of the flow field, a previously developed laser system was used with a high speed camera and a high resolution camera. The following is a description of each piece of the testing apparatus.

A. Acetone Seeder

The configuration of the jet air supply and acetone seeding system can be seen in Figure 1. First, a nitrogen tank is connected to a pressure chamber filled with acetone. The nitrogen enters the pressure vessel through a tube that leads to the bottom of the tank. As the nitrogen enters the bottom of the tank and bubbles through the liquid acetone, the acetone is absorbed into the nitrogen. This nitrogen acetone mixture is controlled by a pressure regulator on the nitrogen tank which is also monitored by a pressure gage on the acetone tank. A hose is connected to the top of the acetone tank to receive the acetone mixture which then leads to a series of valves in the following order: a needle valve, a one way valve, and a solenoid valve. The first two valves listed are for general safety. The electric solenoid valve, however, is used to turn the flow of the acetone vapor on and off. After the acetone passes through the valves, it is connected to the model mount using copper tubing allowing the mixture to flow through the finned body.

B. Wind Tunnel Model

A 3-D model of the generic flight vehicle is shown in Figure 2. The finned body has a 0.5 in diameter and is 4 in long, from the nose to the back of the fins. The transition from the end of the fins to the mount is smooth so that no shocks or expansions are created as to not interrupt the flow field aft of the fins for future experiments. There are four equally spaced fins on the body with a length of 1 in and a height of 0.25 in. The leading edge of the fins is swept from the body to 0.5" at the tip. The nose has a cone half angle of 15°, and the body is hollow to allow for acetone seeding. It is loosely connected to the mount to allow for rotation of the finned body for different orientations of the jet relative to the wind tunnel windows, and three set screws are used to keep the model in place with an EPDM o-ring to seal the connection. The model has eight converging 0.03 in jets arranged in two sets: four located 1 in aft of the nose and four located 1.75 in aft of the nose. Both sets are arranged with a jet located at 0°, 15°, 30° and 45° relative to one of the rear fins. During experiments, all of the holes are plugged using a sandable filler. Only one jet was used for all of the experiments from the 1 in position. The angle of the jet to the downstream fins was not a factor in the composed experiments, because the jet fluid field was observed forward of the fins.

C. Flow Visualization Systems

Initial imaging was done using traditional schlieren imaging using a 15mW He-Ne laser as a light source. The schlieren imaging set-up is a typical z-type configuration [12]. Images were captured using a Point Grey Research Grasshopper IEEE1394. For these images pressurized nitrogen was used to create the jet, and images were captured to compliment and confirm a working test apparatus.

Acetone contained in the jet condenses into small particles upon expansion through the nozzle and mixture with the low temperature, supersonic flow. Therefore, the primary diagnostic tool used herein is a recently developed three-dimensional flow visualization system based on particle scattering. This system produces high-energy visible light at 532 nm in the form of a thin laser sheet, to be scattered by the condensed acetone particles formed in the jet as it penetrates into the cross-stream flow. In this manner, the interface between the jet fluid and the freestream is visualized. 3-D visualization is accomplished by scanning the planar laser sheet through the flow field (as shown in Figure 3), and acquiring multiple 2-D images of the flow throughout the scan. The resulting sequence of 2-D images can then be reconstructed to form a 3-D image of the flow field. In this manner, the structure and interaction of the air exiting the jet with the rest of the flight vehicle flow field can be studied with greater detail than traditional planar techniques.

The unique aspect of this system are its high-speed capabilities, which are made possible using a MHz-rate pulse burst laser, a galvanometric scanning mirror, and a high framing rate CCD camera. Previous efforts have focused on the development and use of the system for flow visualization of other flow fields [see refs. 1, 13,14]. This work is based on the same technique; therefore, a brief description of the system is provided here.

The main piece of instrumentation used in the technique is a home-built pulse burst laser system that is capable of producing laser pulses at repetition rates in excess of 1 MHz over a ~1 msec long window [see ref. 15]. Recently, the laser system has been significantly upgraded with two additional laser amplifiers, enabling the system to generate 20 nsec duration pulses containing approximately 30 mJ per pulse at 532 nm. For 3-D visualization a burst of 68 laser pulses is produced at a 500 kHz repetition rate and deflected off of a 6 mm aperture galvanometric scanning mirror. A long focal length spherical lens located in front of the scanning mirror and a cylindrical lens placed immediately after the scanning mirror is used to form an approximately 500 μm thick laser sheet whose position is determined by the momentary angle of the scanning mirror. All experiments described herein use the same laser output and configuration. The speed of the mirror can be adjusted to yield different scan lengths with each sheet being uniformly distributed along the scan direction. Images are acquired for each successive laser pulse using a DRS Hadland Ultra-68 intensified camera. The Ultra-68 is capable of acquiring 68 images with 220 x 220 pixel resolution at framing rates up to 500,000 frames per second. Thus, a sequence of 68 images can be acquired in 136 microseconds. Additionally, this system is capable of performing high-speed, time-resolved planar flow visualization. This is used to further investigate particular flow features of interest after they have been identified by the 3-D technique. The creation, growth, and interaction of structures can be followed as the jet progresses in time.

Another technique used to generate a 3-D image utilizes a high resolution camera (Cooke Corp. Sensicam QE) with a resolution of 1376 x 1040 pixels. Utilizing the same laser system, this experiment uses a single image to capture 8 swept laser pulses, with each image formed on a different portion of the CCD chip due to the non-orthogonal perspective of the camera. Although the number of planes captured is less than using the Ultra-68 camera, capturing 8 planes in a single image is not limited by the camera's framing rate. Therefore, this set up is not limited by the 500,000 frames per second of the Ultra-68. The only limiting factor is the pulse repetition rate of the laser. Even the speed of the mirror does not matter. In order to sweep the same area the mirror can just be placed further from the wind tunnel. For taking this data, the laser can be pulsed at 10MHz, thus allowing an 8 pulse scan to take place in less than one microsecond. The ability to increase the speed of the laser allows the images taken of the volume to approach being instantaneous. Ideally every plane would be captured at the same time to insure the 3-D image was instantaneous. However, there are problems associated with an increase in the laser pulse repetition rate. First, an increase in this rate will reduce the amount of energy per pulse, and thus limit the signal received by the camera. Also, the laser becomes more difficult to focus the further the mirror is from the flow field. A crucial element to this procedure is the placement of the camera. The illuminated planes in the seeded flow cannot overlap in the field of view. Using previous images of a dot card and the jet from the Ultra-68 camera it was possible to determine an approximate width of the jet. Because this spatial growth was consistent throughout previous experiments, only a small incremental amount was added to the measured width of the jet to assure no overlap. The camera angle was calculated, using simple geometry, at 60° from the wind tunnel. Although there are larger gaps between the planes, having the laser sweep at such a high repetition rate allows the image to approach being instantaneous.

D. Wind Tunnel

All testing is conducted in Auburn University's 4 in. x 4 in. variable area supersonic wind tunnel, capable of running at a range of Mach numbers from 1.5-3.5. The air supply to the tunnel consists of a large 130 psi air tank pressurized using an Ingersoll-Rand SSR compressor, and is passed through a desiccant air dryer before entering the storage tanks. All models are mounted aft of the test section via a C-mount, allowing for variable angle of attack. For this experiment the model was left at 0° angle of attack, with test performed at Mach 2 with a Reynold's number 9×10^6 for the model. All tests were performed with a Reynolds number of 7×10^4 for the jet seeded flow.

III. Imaging

A set of schlieren images was taken to confirm a working model and explore its potential. The jets on the model were produced by high-pressure nitrogen regulated to 50 psi. Figure 4 is one of many images taken. The bow shock created from the jet interaction with the supersonic flow is clearly visible. In Figure 5, two jets are opened with one facing the camera. The wrap around shock from this jet can be seen on both the top and the bottom of the model. Even though schlieren images only capture density gradients, the images taken show the complexity of this flow field.

In order to ensure both the camera and the laser were working properly several volumetric images were taken with the acetone being seeded to the model. First, time-resolved images were taken with the Ultra-68 camera. Structures in the jet flow field could clearly be seen and followed downstream throughout the images. Also, volumetric images were taken with the Sensicam QE. A single image was taken for all 68 laser pulses creating a time-averaged image. This image can be seen in Figure 6. The excess amount of signal received by the camera is visible in this image. A large white glow is all that can be seen of the jet. Although this image is limited, it gives very encouraging results for the ability of the laser when used as a thing sheet.

After this initial assessment was completed, 3-D flow visualization was created through the use of both cameras. Instead of using volumetric illumination, the laser was focused into laser sheets to capture the images necessary to create the 3-D flow visualization. The first set of images was captured using the laser sheets with the Ultra-68 camera. These data sets consisted of 68 images taken from 68 planes along the length of the model. The camera was placed near the wind tunnel in order to acquire images from a near-orthogonal position relative to the plane at the center of the sweep. In order to focus the camera on the laser sheet, a simple macro-imaging technique was used. The long focal length lens initially being used was turned around and placed on a mount in front of the camera. This increased the spatial resolution of the images taken. Images captured were processed in MATLAB and converted to a TecPlot compatible format to create a 3-D flowfield image as seen in Figures 7-8. There are some obvious flaws with the images. In between each image taken the created flowfield appears to squeeze in. This is in fact not happening. It appears to be a problem created by a ghosting effect from the camera, which is essentially a previous image imprinted on the current image. More processing code needs to be further developed to attempt to erase this artifact. From the images it is possible to see the spatial growth of the jet along the finned body. Noticeable blending with the jet and free-stream can be found as well, possibly through the interaction with the counter-rotating vortex pair. This vorticity field will push the jet away from the body and begin to stretch it. The stretching of the jet flow field can be seen in the images, although the jet appears to stay close to the body. This could be due to the low back pressure used to create the jet, or that the particles from the jet were beginning to mix with the free stream. Laser-induced fluorescence would be able to measure the concentration of the seeded flow to determine if this is happening. Although these images provide some insight into the nature of the jet flow, more data is necessary.

Further experiments, capturing 8 planes on a single image with the Sensicam aided in visualizing the flow field. The primary reason for this technique is to escape the limitation of the frame rate of the Ultra-68. However, due to the current test apparatus the scanning mirror could not be placed far enough back to increase the speed of the laser scan. Figure 9 is an example of one of the images captured. No image processing has been completed on this image. Therefore, the planes seen are 60° off orthogonal. Even in the current view it is possible to see the jet being stretched. Again, it is not really possible to see the jet being pushed away from the body, possibly due to what was previously mentioned. Although the laser was not able to be scanned at higher speeds, the potential for this setup is clear.

IV. Limitations of Current Equipment

There are many obstacles to gathering useful data with the current flow facility and experimental arrangement. Most of the problems associated with the experiment revolve around the optical access to the supersonic wind tunnel. Having only 2 windows already severely limits the ideal workspace as seen in Figure 10. For scanning the length of the model the ideal location of the camera would place it directly in the center of the wind tunnel, this is obviously not possible. If a third window was placed on either the top or the bottom of the wind tunnel, perpendicular photos could be captured. These images could also be scanned the width of the jet, rather than the length, allowing for a denser data set to be captured by the limiting 68 images of the Ultra-68. Additionally, the windows also hinder the images taken as seen in Figure 6. The bright spots seen on the left side of the image is due to the visible transmission of the laser through the window of the wind tunnel. The camera has to be placed at an angle so that these reflections do not cover the necessary field of view to capture the jet flow field. The top and bottom surfaces of the wind tunnel are polished metal, which also creates horrible reflections. However, image processing is the only way to remove unwanted light due to these reflections. Also, the current wind tunnel does not have electronic gauges that are constantly monitoring the properties of the flow. New electronic pressure and temperature gauges are necessary to monitor and record these properties.

Another significant limitation is our current high speed camera. The resolution is not high enough to capture the full flow field, and the built-in image intensifier increases shot noise. Also, even though the laser can be pulsed at rates over 1 MHz, the camera can only take images at 500,000 frames per second. At this frame rate particles in the flow field move too far for the images to be combined to create an instantaneous 3-D flow field. Therefore, in order to capture images in a manner to consider the 3-D flow field created with them instantaneous, a faster camera is necessary. Further development of the Sensicam technique is possible to overcome this.

The laser also needs to be updated to capture an instantaneous flow field. In order to capture instantaneous images, as previously stated, the laser sweep needs to be as fast as possible. However, when the pulse repetition rate of the laser is increased, the amount of energy per pulse severely decreases. The intensity of the light reflecting off of the particles would not create enough signal for the camera to create an image. In order to capture images at greater than several MHz, upgrading the laser would be necessary.

Other minor limitations can be found with the current working model. The ability to machine smooth accurate surfaces is difficult at this small of scale (another limitation from the wind tunnel). Even a small scratch on the model when scaled to a full size would be comparable to huge gash. Also, increased ability in the processing code is necessary to gather as much information as possible from the current equipment. More development is necessary to reduce the ghosting problems found in the images as discussed previously.

V. Conclusions and Future Work

There is great potential for creating 3-D images using the current system, and eventually taking 3-D measurements using laser-induced fluorescence. The complexity of the reaction jet flow field proves the necessity for an experimental system to capture this data and the potential collection of high quality data. The data currently obtained lays a foundation for more advanced diagnostic capabilities, and the difficulties involved have been identified. A new finned model with more resemblance to a real world application has been built with pointed leading edges on the fins cut to the quarter chord of cross sections. Also, the fins on the new model are capable of being rotated to any location relative to a single reaction jet on the model. This allows for a more variable model for experiments focused on the interaction between the jet fluid and the fins. Also, the image processing code needs to be updated for the Sensicam QE images to create a 3-D image. Additionally, the effect of Mach number on the flow field will be examined along the full range of speeds, M=1.5-3.5, available in our facility, and the effects of angle of attack with the jets placed in both the leeward and windward orientation.

The long term goals of this project are to create a 3-D laser induced fluorescence measurement [see refs. 2,16]. Many elements in the current work need to be updated before this is possible. The current windows in our wind tunnel need to be replaced with fused silica in order to allow ultraviolet light to enter the wind tunnel. Also, more amplifiers need to be added to the current laser system to increase ultraviolet pulse energy. The current system would not create enough fluorescence signal to be imaged. Once completed, reliable measurements will be created to give a full view of the nature of this flow field as well as data to confirm computational results. Also, this 3-D laser-induced fluorescence technique would not be limited to the reaction jet and could eventually prove to be valuable in many other flow fields.

Acknowledgements

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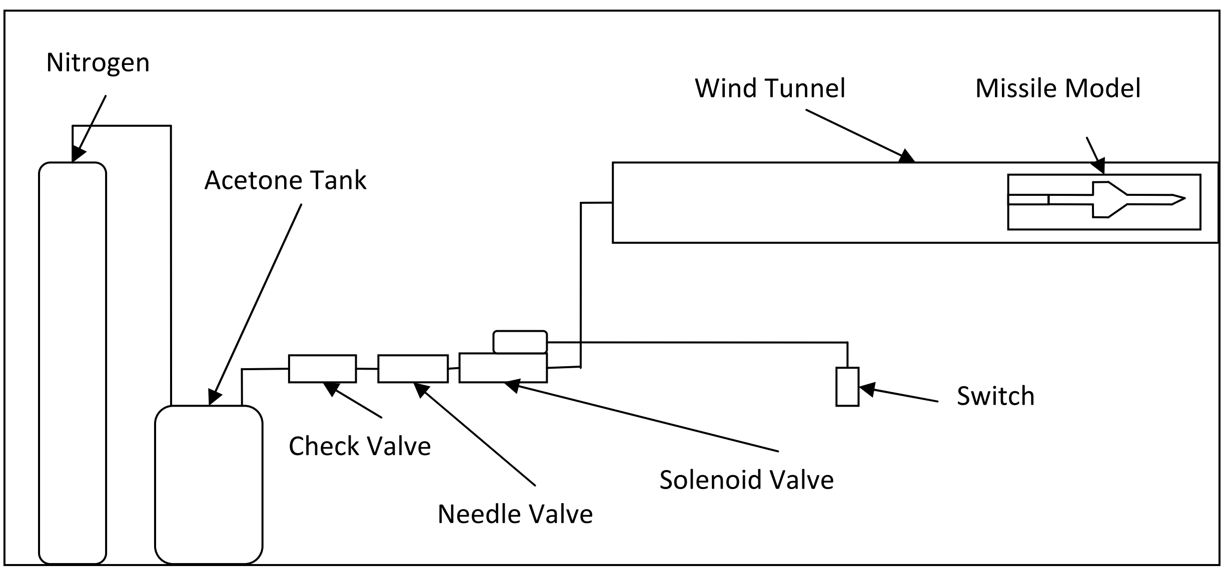

Figure 1: Acetone/Nitrogen Seeder Set-up

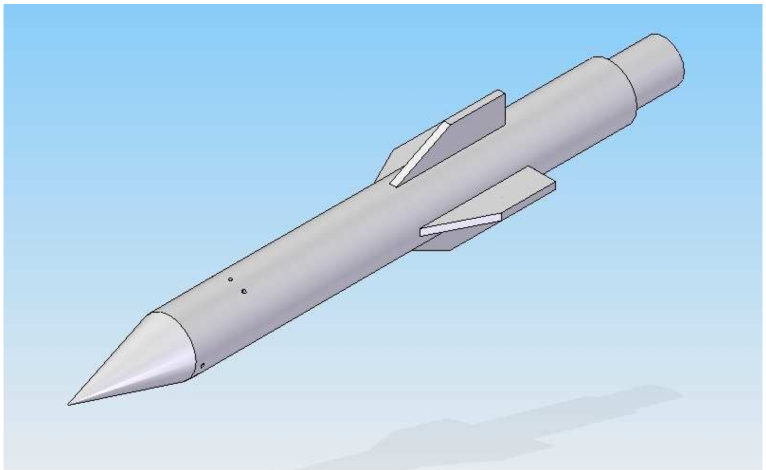

Figure 2: Finned Body Model

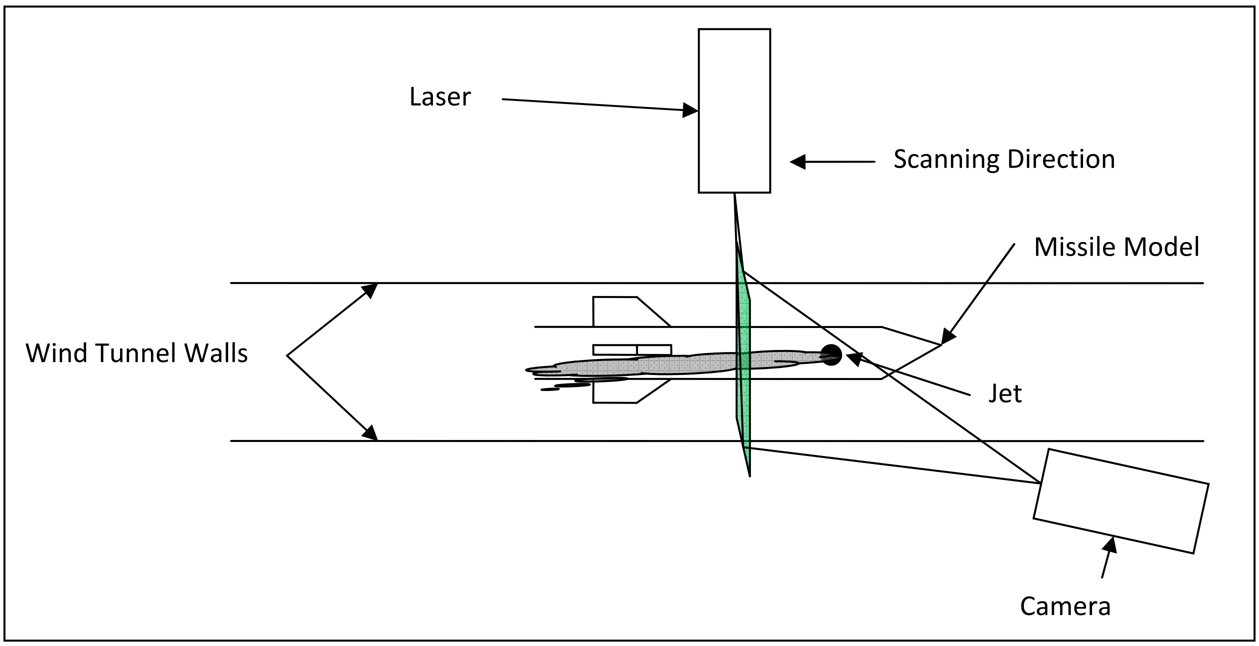

Figure 3: 3-D Flow Visualization Set up

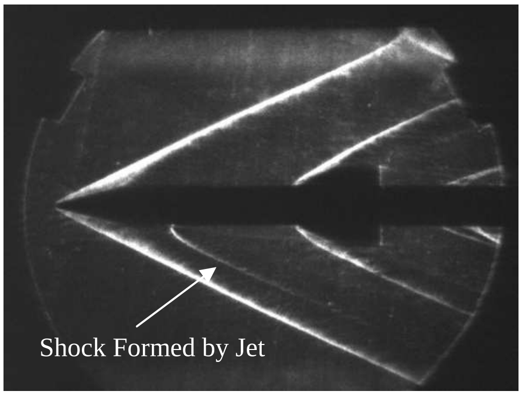

Figure 4: Test with 1 Jet

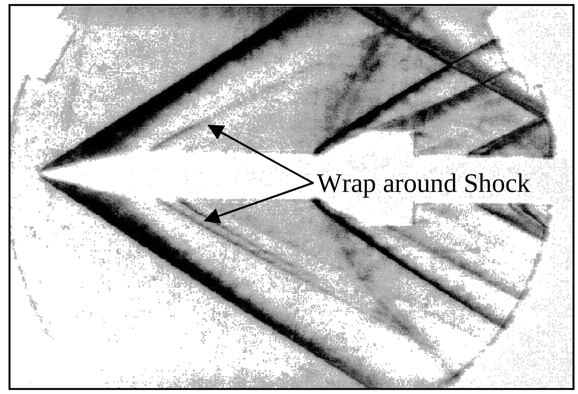

Figure 5: Test with 2 Jets Open

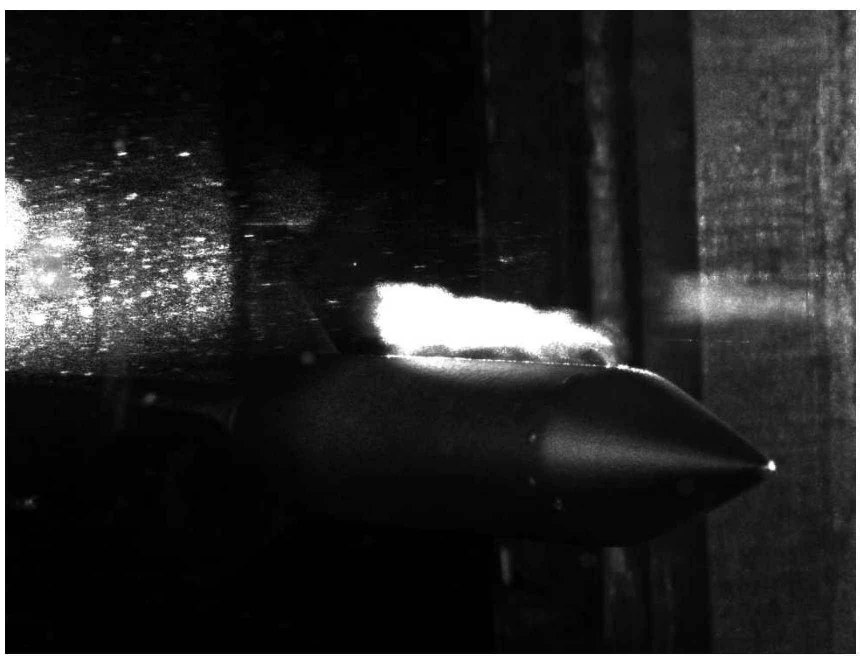

Figure 6: Time-Averaged Sensicam QE Image

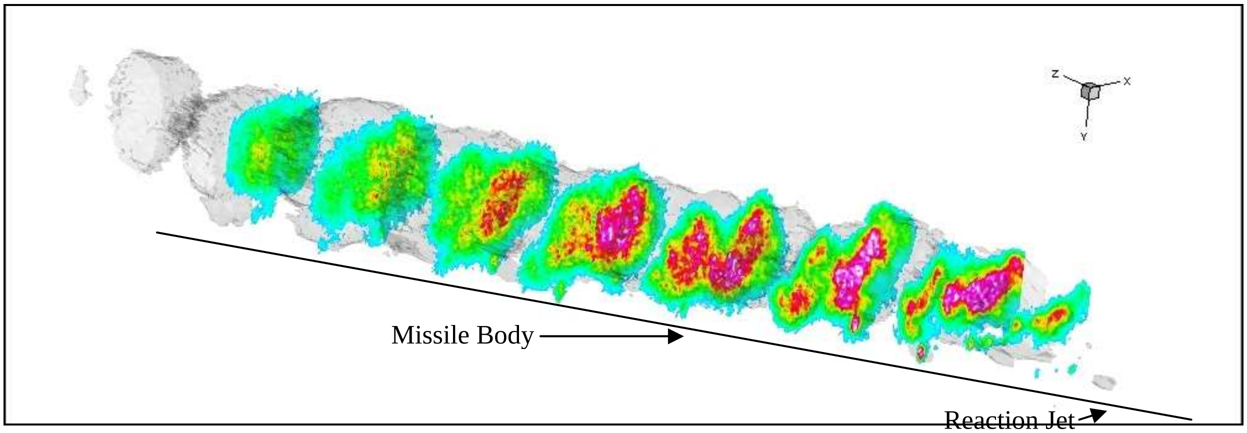

Figure 7: 68 Pulse TecPlot 3-D Flowfield

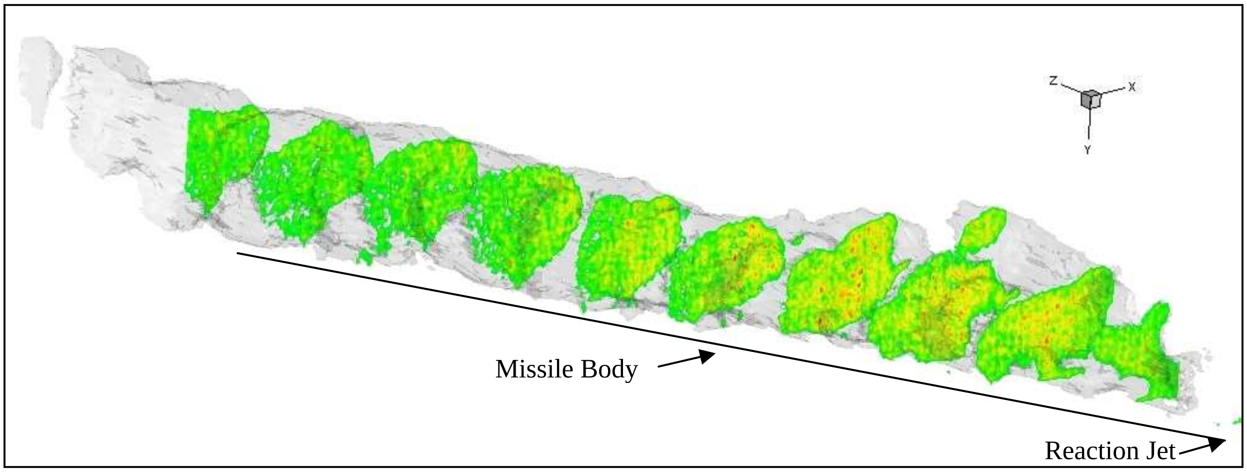

Figure 8: 68 Pulse TecPlot 3-D Flowfield

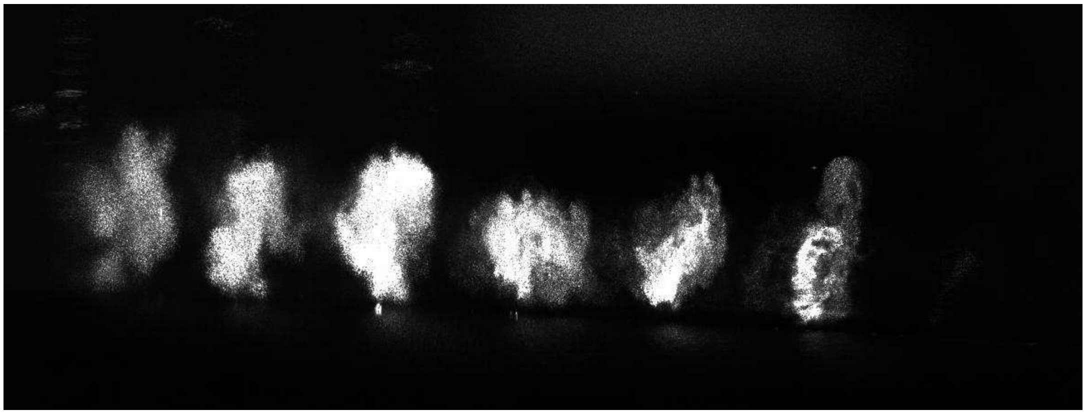

Figure 9: Time Resolved 8 pulse Sensicam QE Image

Figure 10: Wind Tunnel Set-Up for Ultra-68

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