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Particle Image Velocimetry Design & Installation

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May 2016

Abstract

This work will mainly focus on the design, construction, and installation of the Particle Image Velocimetry (PIV) system in the Chemical Hazards Research Center wind tunnel. The PIV system utilizes a Class IV (double pulsed) laser, optics to produce a light sheet, timing circuitry, and a high-resolution camera (with buffered output) to measure a system's velocity (two-dimensional) field by determining the displacement of particles over the time between laser pulses. For maximum mobility and functionality, the PIV system was installed in the center of the tunnel on a moveable cart with the laser and camera mounted to an adjustable support. The instrument support will allow for a variety of obstacle configurations to be studied. Based on the conditions during a recent set of field dispersion trials, basic experiments were performed to demonstrate the viability and versatility of the system. These experiments discussed here consider the fluid dynamics directly behind three different (model) CONEX containers.

1 Introduction & Background

Particle Image Velocimetry is the process of measuring particle velocities utilizing a laser in conjunction with a camera. This process uses the capture sequence of two images taken by the camera in an area illuminated by the laser. In most applications, "tracer particles" or seeding is required to be added to the fluid flow, and the laser illuminates this seeding. [1] At a specified time the laser produces a pulse that illuminates the interrogation region of space, and simultaneously the camera captures an image of the illuminated area. After a designated time delay (Δt), the laser produces a second pulse, and the camera captures a second image. The computer software then uses algorithms to calculate individual particle velocities, which are then compiled into a velocity map over the interrogation region. Figure 1 shows a typical configuration. [1,8]

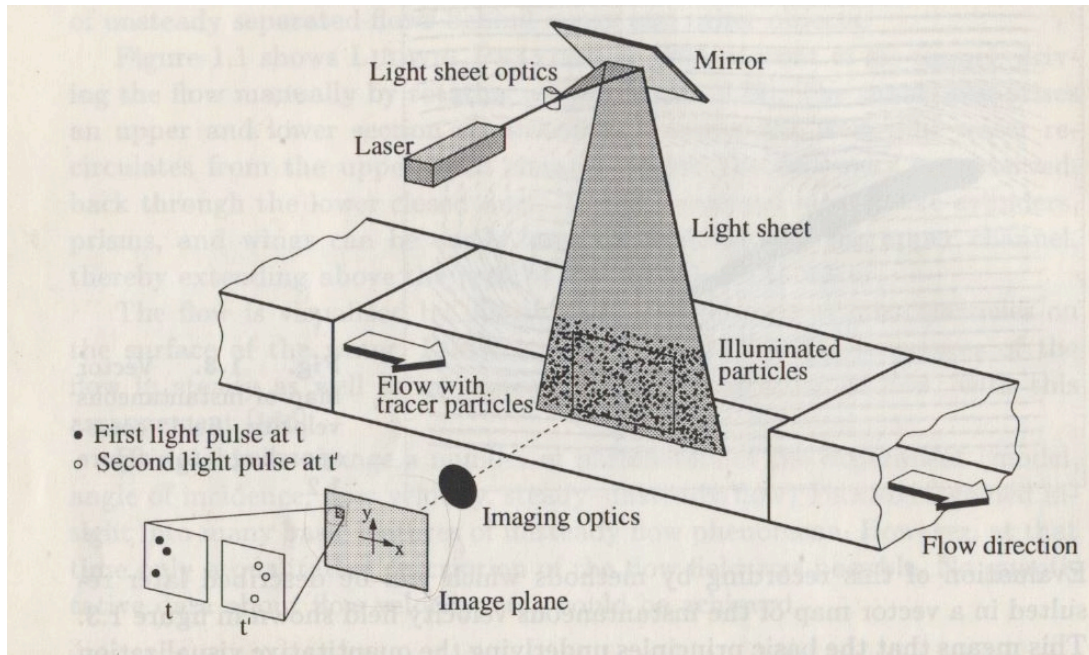


Figure 1. Experimental Setup for Particle Image Velocimetry inside a wind tunnel [5]

The software creates the velocity maps by splitting the entire image into separate interrogation regions and searching for specific groups of particles that match those from the previous image. Once the particle groups are matched to the first image, the software can then identify the particles in the second image and calculate distances. With the known distances, velocities are calculated utilizing the known Δt . One of the most challenging aspects of measuring these displacements is using the appropriate Δt for the given flow. [5, 6]

This type of velocity measurement has advantages over a variety of other methods because it is a nonintrusive type of measurement. This allows PIV to be utilized even in high-speed flow applications where there may be shocks at the boundary layers, which may be affected by the presence of probes. [5]

The objective of this thesis is to deploy the PIV in the CHRC Wind Tunnel, with particular attention to developing techniques that can be used by future students. The PIV system will be used in conjunction with other systems (e.g., 3D Laser Doppler Velocimetry system) to characterize the flow during experiments.

To show the versatility and functionality of the PIV system, a series of experiments was conducted to look at the fluid flow around a series of small buildings. The buildings investigated were a scale model of a single CONEX container as well as a tower made from CONEX containers. The CONEX tower was investigated at two separate scales, 1:25 & 1:50. The CONEX configurations were modeled after those used in the Jack Rabbit II field trials conducted in 2015. [12] Typical flow structures around an obstacle such as considered here are shown in Figure 2.

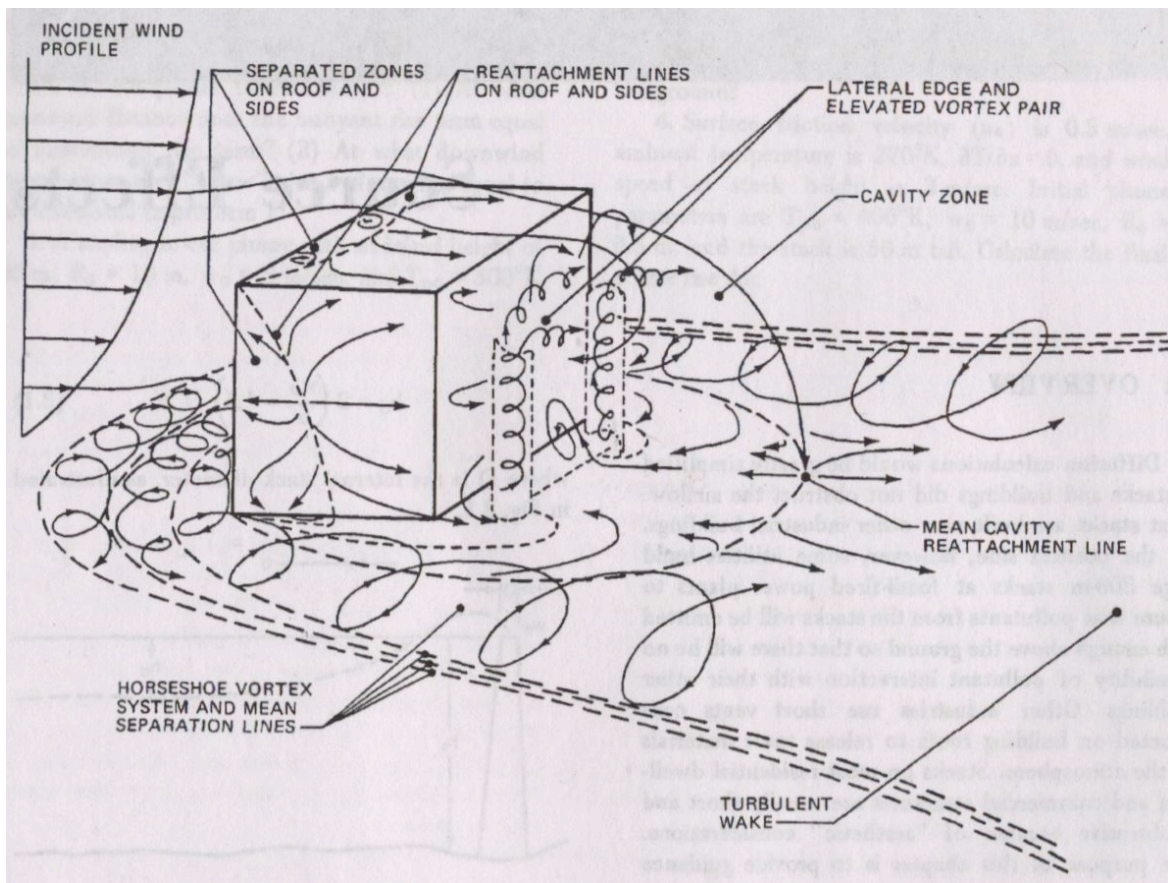


Figure 2. Model of flow near a sharp edged structure [3]

Individual structures, such as the ones being tested, are assumed to be sharp-edged buildings. These sharp-edged structures have been shown to exhibit distinct flow characteristics involving cavity creation, disturbed wakes, reattachment zones, and turbulence based on flow characteristics. Figure 3 below shows a simplified drawing of the cavity directly down stream of

the obstruction. Note that the same region is depicted in three dimensions in Figure 2. The PIV system used in this work produces measurements of the velocity field in a similar manner as depicted in Figure 3.

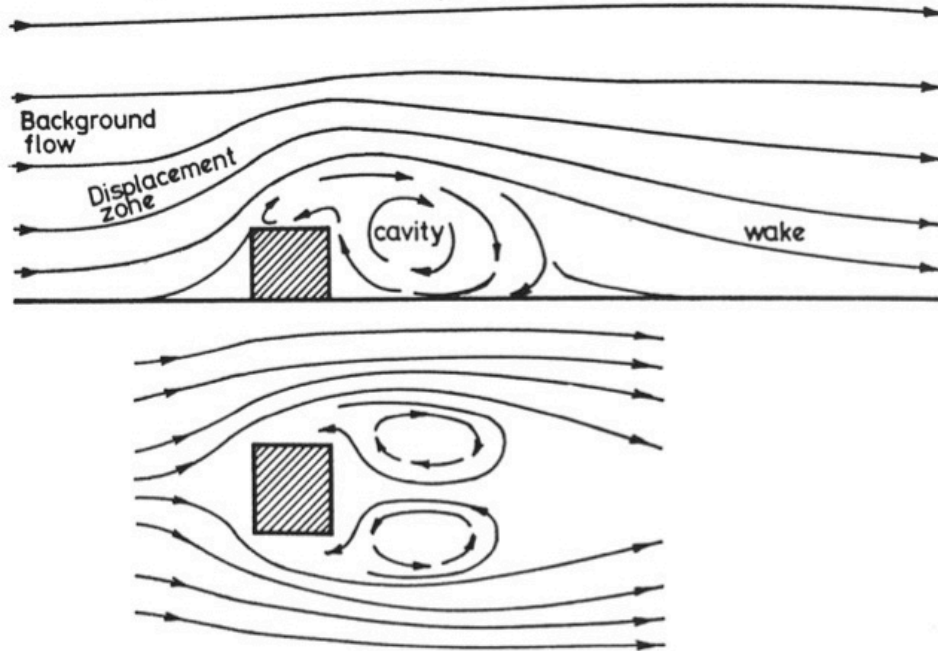


Figure 3. Simplified schematic of flow around sharp-edged buildings [4]

2 Design Requirements & Experimental Setup

An instrument mounting system was designed installed in the tunnel for the PIV system. The basic processes to use the PIV were also developed for the application considered here. The major advantage of the wind tunnel is the ability to accommodate large-scale models. Consequently, the PIV system needed to be designed so that it could be easily moved to any point inside the tunnel. To achieve this flexibility, the PIV system was mounted onto a rail system that was attached to a mobile platform located underneath the tunnel. The PIV system also has the ability to be rotated a full 360° by using a rotation table. The adaptor pieces were designed to connect the laser support system to the camera. Once the design and fabrication process was finished, the platform was installed underneath the tunnel by removing several of the removable

2'X2' tiles. With the cart in place the Integrated Circuits and Electronic boxes (ICE Units) were then mounted to the platform and the laser head attached to the rail extending up into the tunnel. This setup will allow a free range of motion in all three directions of the coordinate plane: X, Y, and Z. To provide for maximum flexibility, the laser can be repositioned by simply loosening bolts on the brackets and retightening after the laser is repositioned.

The only equipment inside the wind tunnel operating area is the rail support system and laser head. The ICE Units are housed underneath the tunnel floor tiles on the platform, while the computer tower & synchronizer were installed underneath the tunnel skirt at the edge of the tunnel. For optimal operation there were two monitors installed, one inside the tunnel that can be placed underneath with the ICE Units and the second inside the control room. This setup allows for calibration to be done inside the tunnel with the first monitor and large data collection or processing done with the second monitor.

During all testing the wind tunnel was operating at a fan speed of 40 RPM, which corresponds to approximately 0.23 m/s wind speed inside the tunnel, and all data was taken using a Δt of 6,000 μs . This allowed for the appropriate seeding density to be maintained during data collection. The Reynolds Number for each of the three structures was determined.

$$Re = \frac{V*L}{\nu} \quad \text{Eq. (1)}$$

where V is the free stream velocity, L is the characteristic length (height) of the structures, and ν is the kinematic viscosity. Table 1 below shows the corresponding Reynolds Numbers.

Structure	Reynolds Number
1:25 Conex	1500
1:25 Conex Tower	4500
1:50 Conex Tower	2200

Table 1. CONEX Container Reynolds Numbers

3 Data Collection and Operational Procedures

Once the system was properly installed and functioning, the first step in data collection was to determine the seeding needed to have sufficient statistical correlation to produce valid velocity data. An approximate seed density of 5-15 particles in each grid section or interrogation region is necessary for the Insight 4G software to appropriately read the particles. [7,11] Figure 4 below shows an image of the approximate range of appropriate seeding densities. To effectively use the PIV, it is helpful to develop a sense of the seeding density that will produce good velocity data by quick visual inspection of initial images. [11] In all of the photographs included here, the mean flow is from left to right in the picture.



Figure 4. Approximate Seeding Density Required [11]

With the appropriate seeding established, calibration of the camera and laser can begin. The first step is to establish the correct camera focus, which depends on the area of interest for measurements. Procedure E. in Appendix 1 discusses a step-by-step process to focus the camera on the seeding present. Figure 5 below shows the correct camera focus on seeding that is required for accurate data. [7,9] If the camera is unfocused, there will be an excess of bad vectors present during initial processing.

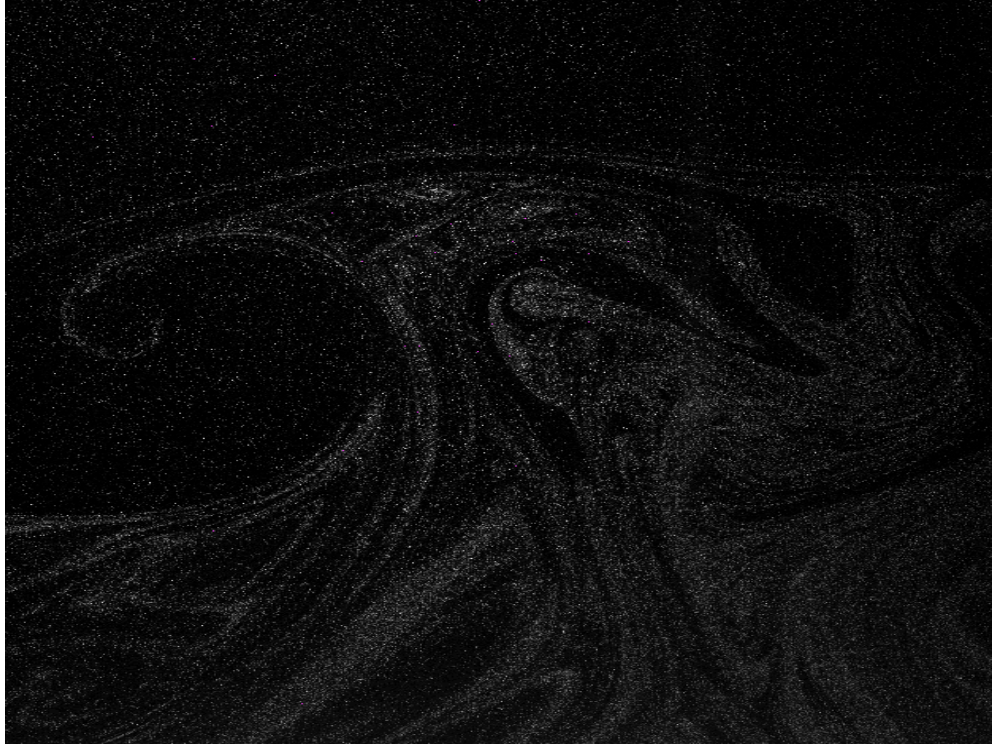


Figure 5. Seeding With Appropriate Focus

It is important to note that changes in focal length are extremely sensitive. There is also a time lag between a camera setting change and its subsequent display, so it is helpful to pause between changes to ensure up-to-date settings are used. When starting the process of focusing the camera, an initial aperture setting of 1.8 on the camera ensures the camera receives adequate light during calibration. During data collection, it is recommended that the aperture setting be in the range of 5.6-8 because higher laser energy coupled with smaller aperture settings will generally result in better data.

Insight 4G is the software component of the PIV system which calculates the velocity field. The software allows the user to set a variety of parameters and interest points for the camera and laser. Insight 4G includes flow field calculations to cut down on the uncertainty percentages that had plagued previous PIV applications. [2,8] During data collection, vector analysis should be utilized periodically to ensure valid data is being taken. It is recommended to obtain “Good Vectors” on the order of 80% or greater of the estimated vectors for viable data,

and this percentage increases, the quality of the data improves (95% or greater provides the best results). In the example shown in Figure 5, there were a total of 97% good vectors once processing was complete. [8,10,11] (Refer to Figure 20 in Appendix 2 for the Vector Statistics)

Once the first set of data was collected, simple processing was done to verify there were at least 80% “Good Vectors” identified by the software. To meet this requirement, adjustments can be made in: seeding density, seeding focus, camera angle, light pollution, Δt , and laser energy. The most effective methods to improve the measurements are the initial calibration settings, seed density, and camera focus. If there are insufficient seed particles in the area of interest (less than 5-15 particles per grid) the software will have a more difficult time identifying seeding in the flow field calculations. If the camera is not in focus on the area illuminated by the laser pulses, then the seeding will not be properly illuminated. If both the seed density and focus are appropriate, the time between pulses, Δt , would be the next most important factor. It is recommended to start with a Δt close to 0, generally about 10 μs . With the Δt this low it should essentially freeze the particles from Frame A to Frame B. From 10 μs start increasing the Δt by a factor of 10. Once small particle movements are detected, Δt can be changed by a factor of 2 to 4 until particle movements are approximately 25-50% of each grid interrogation area. For all experiments conducted here, the Δt was 6000 μs . [11]

Using the Insight 4G software, images can be taken as a single pair or sequences comprised of pairs of images. This versatility allows the user the ability to capture instantaneous flow structures, and flow structures over a period of time. (Procedures A through H in Appendix 1 discuss the process for image collection.)

Once the raw data (as image pairs) are collected, Insight 4G then processes the information to generate the velocity vectors. Under the Processing tab, there are several processing options including a Macro option that saves all processing settings for future use once created. The Spatial calibration setting is based off the distance measured utilizing the camera;

(Procedure F in Appendix 1). Light pollution (including scattered laser light) can be removed from images using the pre-processing options in the software provided there are at least 10 image pairs in the data set. (See Appendix 2 Figures 16 and 17 for Pre-Processing settings). The software generates an image of particles or light that remains throughout the 10 image sets and then subtracts that constant from all the frames to create a cleaner data set that is then processed for velocities.

The processing mask allows the user to select only a small region of the image to be fully processed for velocities; this is useful if there are areas of the data that have inherent issues such as low seeding density or blockage. The Processing setting allows the user to alter the processing method taken by the software. Finally, the Post-Processing allows the user to change the local velocity vector settings and tolerances. Figure 21 in Appendix 2 shows the appropriate Post-Processing settings.

During the initial data collection steps when verifying images are of sufficient quality to produce valid data, limiting settings to Spatial Calibration, Processing, and Post-Processing will speed the alignment process and be representative of the quality of data collected. However, a Processing Mask can be applied if there are large areas that will be removed during Pre-Processing that are degrading the data.

Tecplot is another useful tool built into the Insight 4G software that allows the user to graph the velocity field. Figure 6 below shows an example of a Tecplot velocity gradient with the darker red regions representing high velocity and the yellow regions are relatively low velocity.

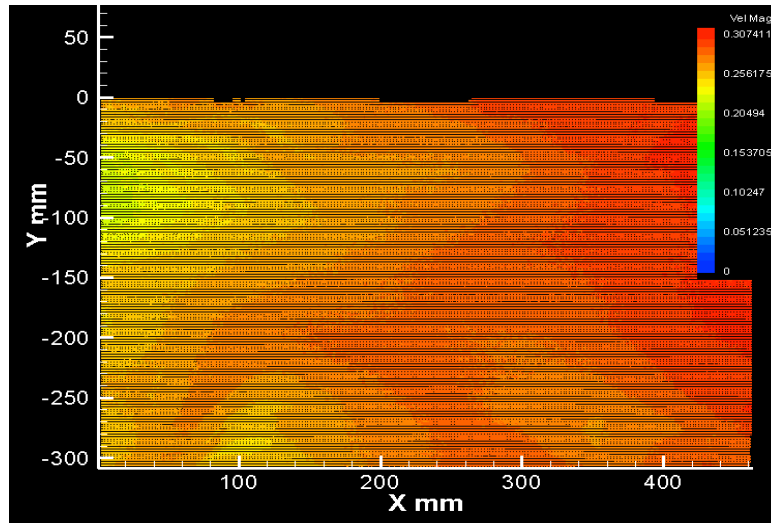


Figure 6. Tecplot Velocity Gradient

4 Data Discussion

Sets of 10 image pairs were obtained for each of the three model CONEX containers. These image sets were used in conjunction with the Insight 4G software to process the velocity flow gradients represented in Tecplot. Figures 7-9 below show a baseline flow structure for each of the three containers. (See Appendix 2 for images without velocity vectors.) Note that the flow patterns visible in the photographs are a consequence of the upwind seeding and do not reflect the flow field generated by the models. As indicated earlier, the mean flow is from left to right in the photographs. In all of the photographs of the model CONEX containers, photographs are taken immediately downwind of the model. The model and camera were placed to reduce light pollution from scattered laser light.

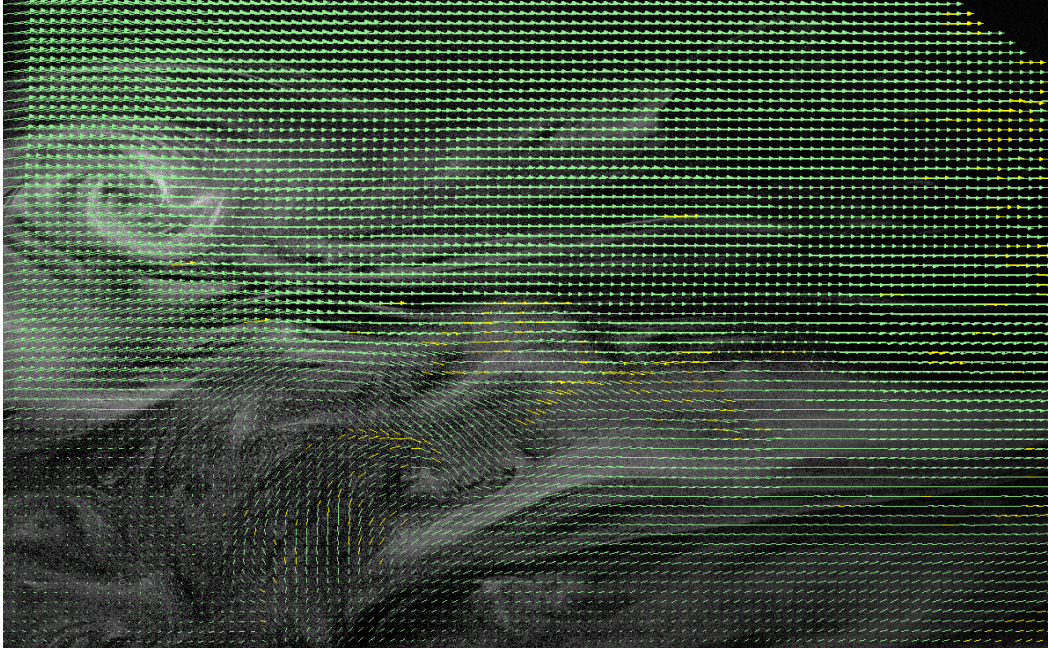


Figure 7. Basic CONEX Model

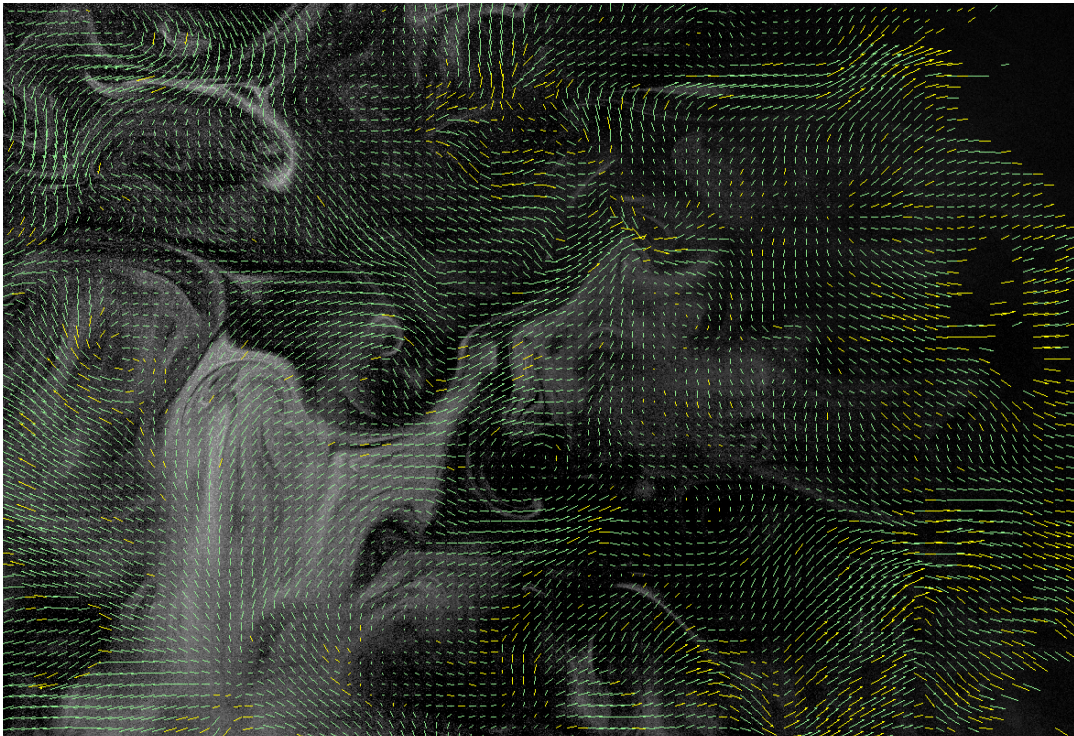


Figure 8. CONEX Tower 1:25 Model

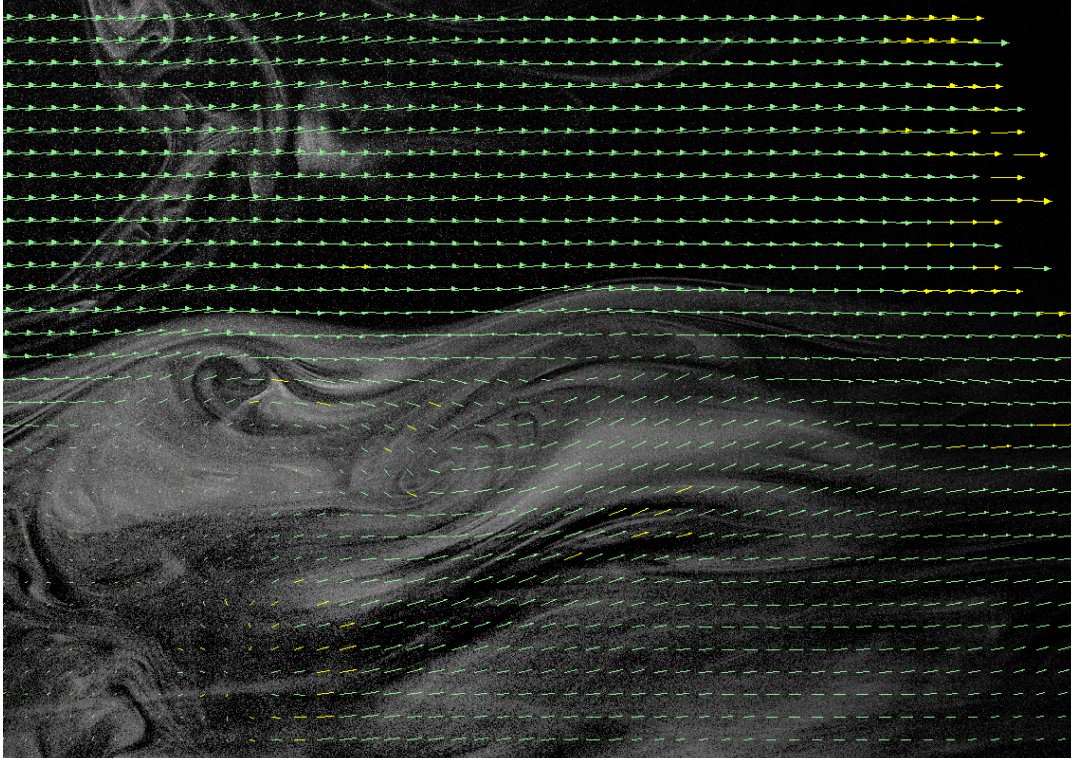


Figure 9. CONEX Tower 1:50 Model

The vectors shown in this first set of images show the approximate direction and magnitude of the velocity for the particles in that region. The average velocity gradients for the above images are seen in Figures 10,12,14 below. The second sets of images are the velocity gradients with streamlines to assist in visual identification of the flow structures such as cavities. (Figures 11,13,15)

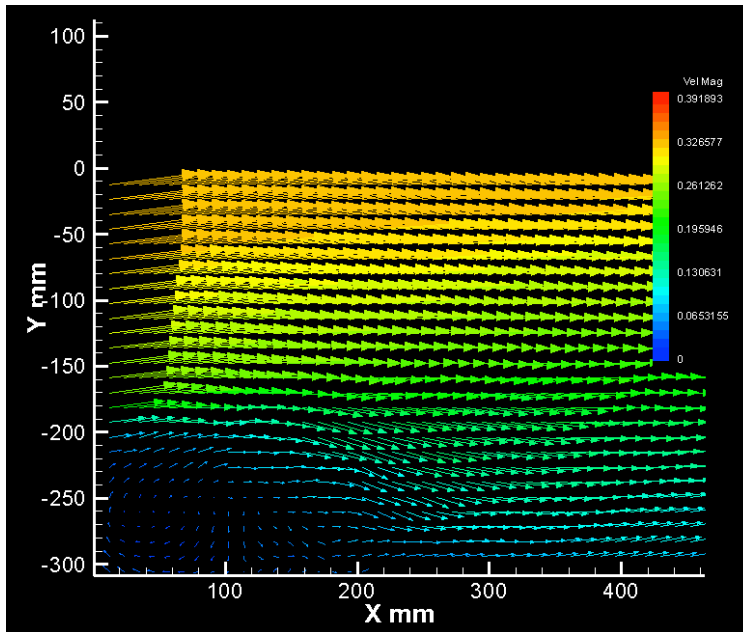


Figure 10. Basic CONEX Model Average

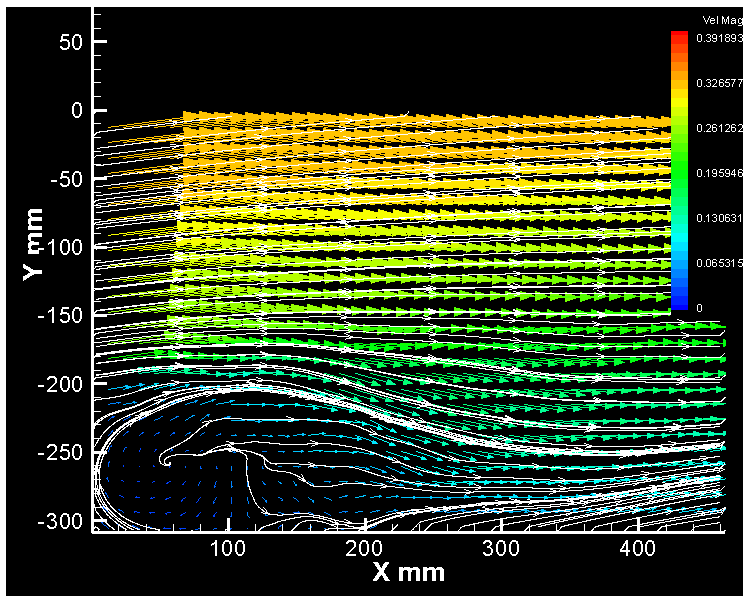


Figure 11. Basic CONEX Model Average with Streamlines

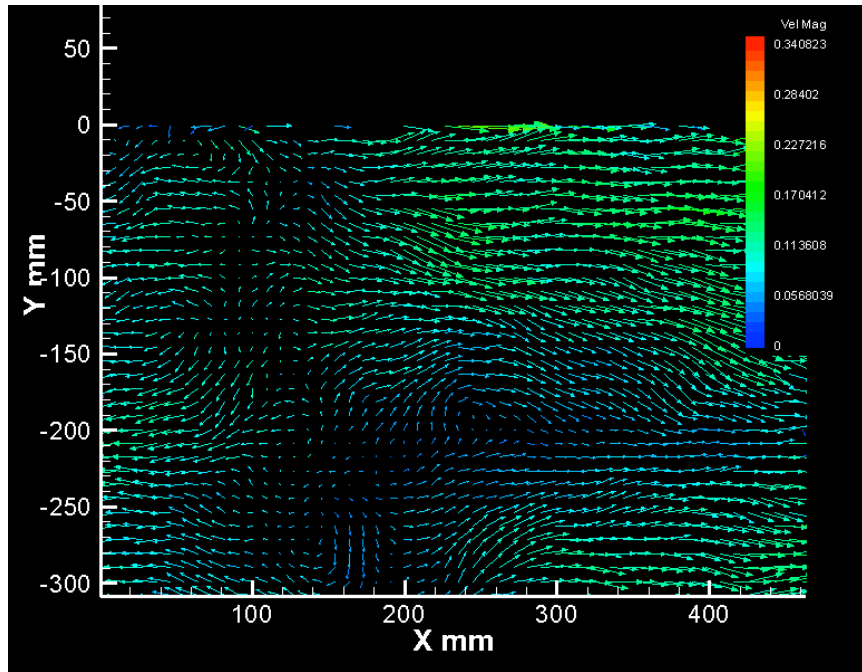


Figure 12. CONEX Tower 1:25 Model Average

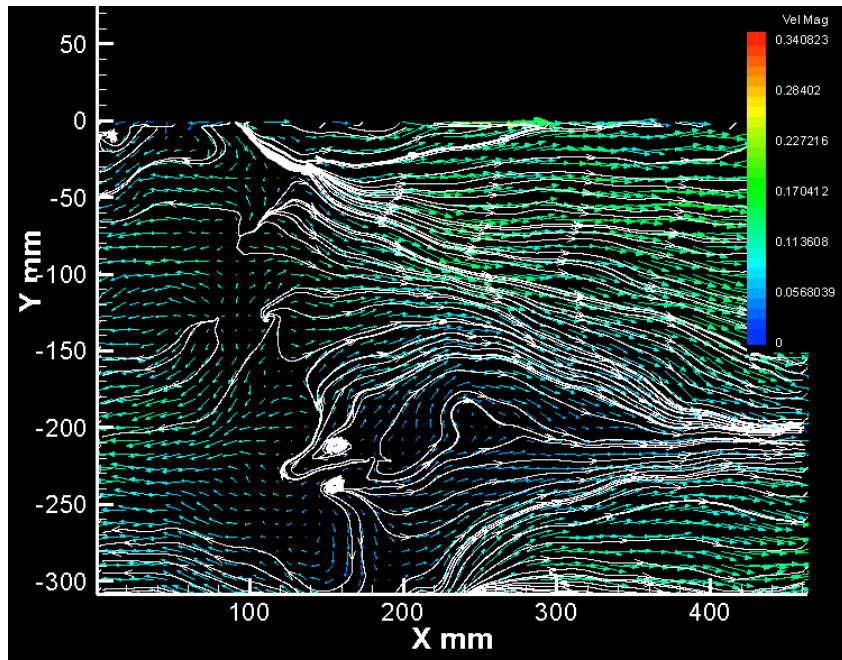


Figure 13. CONEX Tower 1:25 Model Average with Streamlines

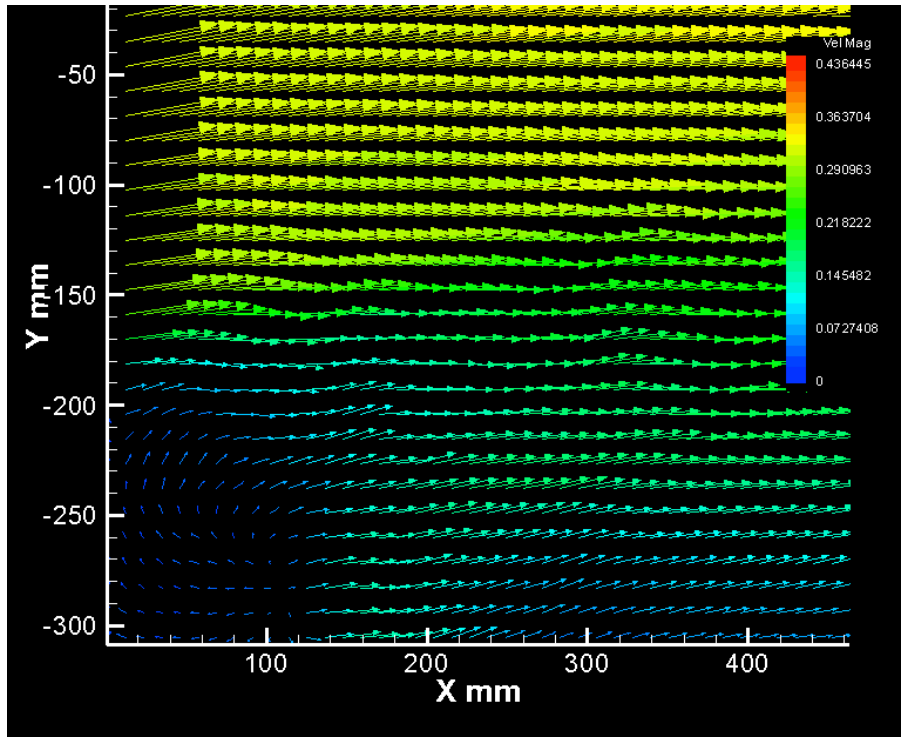


Figure 14. CONEX Tower 1:50 Model Average

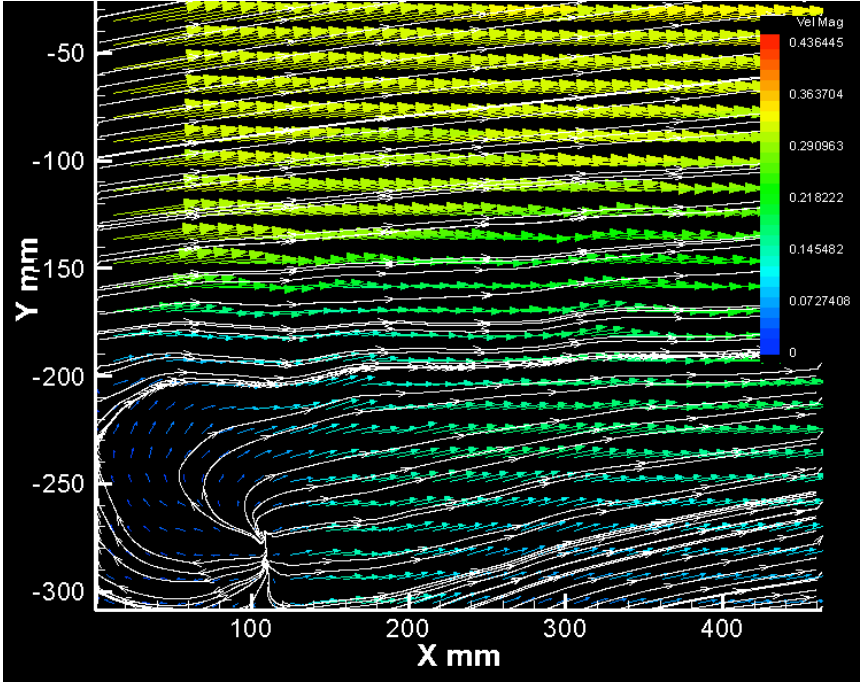


Figure 15. CONEX Tower 1:50 Model Average with Streamlines

The airflow field is relatively similar in the Basic 1:25 CONEX Model and the 1:50 CONEX Tower. This can easily be seen in comparing the average velocity gradients plotted in Tecplot. Figures 11 and 15 show a generally uniform upper layer with complex structures near the wind tunnel floor. In contrast, Figure 13 shows complex flow structures generated throughout the entire region, directly caused by the larger amount of flow disruption the larger tower created. In both the Basic 1:25 CONEX Model and the 1:25 CONEX Tower seen in Figures 11 and 13, it is interesting to note the cavities created directly after the structures by an upwind displacement zone. Zones similar to this can be seen in the 1:25 CONEX Tower model as well, but the structures are more complex. Recirculation zones were expected based on previous experiments in flows around sharp-edged buildings as discussed earlier. [1,3,4]

Based on the data received the average velocity for flow structures for all three models is in the range of 0.2 – 0.4 m/s.

6 Conclusion

A PIV system for measuring two components of the velocity simultaneously in a plane has been installed in the CHRC wind tunnel. The installation allows the PIV measurements to be made in any area of the tunnel. Preliminary investigation of the flow field around three simple rectangular prism models was made, and the results are consistent with observations of other investigators. For the range of experimental conditions anticipated, the PIV system can produce accurate measurements of various flow parameters including mean flow and turbulence. The ability to measure these variables for any given experiment allows future researchers the ability to study different obstacle configurations with the system. The structures tested here showed consistent behavior with known behavior including overall flow structure and formation of recirculation zones. Further testing may be done to show the mean cavity reattachment line over longer data collection periods.

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Appendix 1

Procedures: Maintenance, basic startup, shutdown, software usage, hardware setup, software settings, safety precautions.

Laser Operating Procedures

A. Preparing the Cooling system

1. Remove each ICE (Integrated Control Electronics) reservoir cap
2. Fill each reservoir with distilled water. Check the coolant level windows. The water in each reservoir should now be level with the line marked “MAX”.
3. Turn the ICES ON using the AC Mains power switches on each ICE back panel. “|” is ON, “0” is OFF.
4. Turn the key switches on the front panels to ON “|”.
5. The pump inside each ICE turns on to begin the coolant flow. This starts filling the coolant lines, lowering the fluid level in each reservoir.
6. Use the pump control switch to override the float switch to run the pump during filling. To do so, press and hold the switch labeled “Pump Cntrl” located on the back of each ICE.
7. Add additional coolant to fill each reservoir to “MAX”.
8. Verify that there are no air bubbles in the coolant lines, to avoid laser reflector damage. Cycle the power by turning the main switch off and on several times to remove air bubbles from the Laser head. Elevating the rear of the laser head several cm may aid in removing trapped air from the laser head.
9. Add more coolant as needed to fill each reservoir to “MAX”.
10. Replace the reservoir caps. The system is now ready.
11. **Note:** This procedure only needs to be done after each flushing of the cooling system liquid.

B. Laser Operation Overview

1. Follow all appropriate safety procedures described in the safety training and safety manual.
2. Turn the Mains Power switch ON “|” to supply AC mains power to the system.
3. Turn the Key Switch to ON “|” to apply main AC power to the ICE. The power indicator illuminates to show that AC power is ON. The key is not removable when in the ON position. After approximately 10 seconds, the laser is initialized and ready for operator control.
4. Select the Trigger Termination impedance setting by pressing the button to toggle the 50- Ω Termination setting on or off.
5. The laser can be controlled by the following modes of operation:
 - Manual operation using the ICE Control Panel
 - Remote operation using an external computer connected to the ICE via RS-232.
6. Utilizing the Trigger Source button, select the appropriate trigger source based on experimental setup.
7. Choose the internal flashlamp frequency by pressing the Frequency Button to select either “SINGLE” or “Max Hz”.
8. Utilize the Energy Selector button assembly to adjust the Laser Energy.
9. Push the Electronic shutter button to disable the shutters on the Laser Head. (Caution: the Laser should be treated as capable of lasing when the shutter is in the Open Position).

10. Press the Run/Stop button in the center of the Energy Selector button assembly to initiate Lasing.

C. System Warm Up

1. Follow Procedure appropriate fan procedure to warm up the tunnel fans.
2. Turn the Mains Power switch ON “|” to supply AC mains power to the system.
Note: Refer to Figure 27. for ICE Unit Control Panel diagram.
3. Turn the Key Switch to ON “|” to apply main AC power to the ICE. The power indicator illuminates to show that AC power is ON. The key is not removable when in the ON position. After approximately 10 seconds, the laser is initialized and ready for operator control.
4. Without initiating Lasing, allow the fan & PIV system to run for approximately 1 hour before any data is taken.

D. Starting Insight 4G

1. Ensure prior to starting the Insight software:
 - The Synchronizer is connected correctly and on.
 - The Camera is connected and plugged in.
 - The laser ICE Units are on and not Lasing.
2. Open the Insight 4G software. **Note:** There will be a dialogue box asking permission to allow Insight 4G to make changes on the computer; select YES.
3. **Note:** There should be no error messages with the Insight 4G program upon opening. If there are errors close the program and ensure all connections between the Synchronizer, Computer, Laser, & Camera are correct, and then restart the computer. Once the computer has fully loaded, turn the synchronizer back on and open Insight 4G. The synchronizer should now read “Keypad disabled system under software control”
4. On the Experiment tab select the appropriate Experiment & Run. **Note:** The current Experiment & Run are highlighted in yellow.

E. Focusing on seeding

1. **Note:** For most of the Focusing steps the tile directly above the ICE units will be removed; take appropriate safety measures to avoid tripping risk.
2. Follow Procedure “B. Laser Operation” to ensure laser is set to the following settings:
 - Frequency: Max Hz (Laser 1 should be set to 2ω)
 - Trigger Source: INT LAMP / INT Q-SW
 - Q-Switch: Engaged
 - Shutter Control: OFF
 - OSC 1: Lowest Energy setting of 2
 - AMP 2: Maximum Energy Setting of 20
 - AMP TRIGGER: OFF**Note:** A yellow light signifies engaged & no light signifies disengaged.
3. Ensure Camera is set up correctly at a 90° angle from the laser light sheet.
4. At this point initiate seeding inside the tunnel.
5. Ensure all safety signs are posted correctly and all doors are closed to the wind tunnel room to mitigate incidental lasing.
6. Turn off all lights inside the wind tunnel room, the control room, conference room, shop, and North East small wind tunnel room.
7. Utilize the monitor inside the wind tunnel to conduct all calibrations and focusing.

8. Remove the camera lens cap.
9. Ensure camera settings are as follows:
 - Aperture: 1.8
 - Focal Length: Approx. 0 ft
10. In the Insight 4G software navigate to the capture tab located in the bottom left of the menu. Ensure the Capture tab settings are as follows:
 - Application: PIV
 - Exposure: Free
 - Capture: Continuous

This will allow the Camera to continuously capture images during focusing.
11. Press Capture.
12. Disable Shutters on Laser head by pressing the Shutter Control Button on each ICE Unit. (Laser should now be treated as Lasing could happen at any time.)
13. Toggle the power button on each ICE Unit to initiate Lasing. **Note:** Laser will take approximately 8 seconds to engage lasing once power is toggled on from an off position.
14. At this time Emission Lights on each ICE Unit and Laser Head should be flashing.
15. Ensure lasing is occurring in the area of interest and proceed to increase Laser Energy by the energy selector on each ICE Unit. It is recommended to increase energy slowly to avoid over exposure to the camera.
16. Over exposure to the camera is represented by a magenta coloring in the image and large amounts of magenta will damage the camera. **Note:** If large amounts of magenta are present in the image immediately: decrease laser energy, cap the camera lens, or increase aperture number on the camera.
17. As the energy is increased on the laser, small amounts of magenta will appear. Once magenta starts to appear increase the camera aperture by one setting. Ex. 1.8 to 2.6
18. Once the laser is at approximately 1/2 energy or greater the particles should be sufficiently illuminated to then start focusing the camera.
19. Carefully increase the focal length setting on the camera lens to focus on the particles in the light sheet by watching the monitor. **Note:** This setting is extremely sensitive and focusing should be done at extremely small changes at a time. There should also be a minor delay in each incremental change to allow the system to capture an image of the new focal length setting to be seen on the screen. It may help to go past the optimal focal length setting & then back track to narrow down the correct setting.
20. At this time the particles should be sufficiently in focus. Refer to Figure 4 for approximate focusing requirements.
21. Press Stop to cease image capturing.
22. Re-engage the shutters on the laser.
23. Place the wind tunnel monitor underneath the floor with the ICE Units.
24. Utilizing the trigger source button transfer each ICE Unit to the Ext Lamp / Ext – Q SW setting to be under software control.
25. Using the energy selector pad raise each ICE Units OSC 1 & AMP 2 energy levels to maximum.
26. Ensure the Amp trigger button is enabled. **Note:** The laser energy levels will be controlled within the software so maximum settings on the physical units are required.

27. Since the Laser is now under software control, toggle the power button and disable the shutters on each ICE Unit. **Note:** The laser should be treated as if lasing could occur regardless of software control.
28. Change the camera aperture setting to 5.6.
29. Replace the removed floor tile and tighten each of the four screws to ready the system for data collection.

F. Spatial Calibration

1. Once the system is ready for data collection, place a known object length to be used during spatial calibration. (Such as a ruler)
2. In Insight 4G under the Capture Tab ensure the settings are as follows:
 - Application: PIV
 - Exposure: Free
 - Capture: Single
3. Capture a single set of images for the known object.
4. In the Processing tab select the Spatial Calibration Setting.
5. Under the “Measured Tab” select the measure option.
6. Measure a known distance on the generated image to calibrate the distances in Insight 4G.

G. Data Collection (Single Image Set)

1. At this point the system is ready for large-scale data collection.
2. The camera should remain in the position it was calibrated for to retain the correct focusing on particles in the area of interest.
3. Set all experimental conditions inside the tunnel.
4. On the Experiment Tab in Insight 4G select the appropriate experiment and create a New Run for data collection.
5. On the capture tab in Insight 4G ensure the settings are as follows:
 - Application: PIV
 - Exposure: Synchronized
 - Capture: Single

Note: This type of capture will capture a single set of images.
6. In Insight 4G set Laser Energy Settings to High.
7. Press capture. **Note:** The Laser and Camera should synchronize and capture two separate images. If Frame A or Frame B is completely black, simply press capture again. If problem persists re-enter the Δt value & open the timing setup menu and hit apply.
8. To verify the “Good Vectors” percentage, open the Info menu directly above Fram LA & LB.
9. Select the Vectors option.
10. Select Vector Statistics.

H. Data Collection (Image Sequence Set)

1. To capture a sequence of images follow Procedure G for single image set but set the Capture Tab Settings to the following:
 - Application: PIV
 - Exposure: Synchronized
 - Capture: Sequence

2. Open the Image Sequence Menu and select the appropriate number of image sets and beginning image number.
3. Press capture.

I. Processing Images

1. To begin processing open the image to be processed.
2. Open the processing tab.
3. Select the appropriate processing options pertaining to the amount of processing desired.
4. Processed images will appear in the Analysis portion of the experiment tree found in the Experiment tab.

J. Clearing Wind Tunnel of Seeding

1. Once data collection is finished clear the wind tunnel of seeding.
2. Turn off air to the atomizer by turning the valve located at the SE side of the tunnel.
3. Open the hall double doors that are blocked by a hanging keep out chain located in the SW side of the wind tunnel room.
4. Open the door leading to the electronics room on the Eastern wall of the Wind Tunnel Room.
5. Open the hatch that leads to the shop on the SE wall.
6. Turn the Shop roof fan on by pushing start on the control panel located on the northern wall of the shop near the hatch.
7. Turn Wind Tunnel fans up to 90 RPM or greater.

Laser System Maintenance

K. Basic Maintenance Procedures & Recommendations

1. Refer to Figure 28 for draining procedure.
2. Draining should occur approximately every 3 months.
3. Drain the ICE Units, Laser Head, and Lines if the system will be placed idle for an extended period of time.
4. The system should be turned on and pumps run at least once a week.
5. Lasing should be initiated once a week for a minimum of 10 minutes to maintain crystal functionality.
6. Always use both lasers while taking data to avoid uneven wear.
7. Change the deionization filters once a year. See Figure 29 for changing procedure.

Safety Hazards

- Class IV Laser
- Falling objects
- Confined space

Items to be noted in Safety Training

1. There is a U shaped lock for the glass double doors leading from conference to the miniature tunnel room that needs to be used during laser operation until the PIV system is installed into the main tunnel.

2. Basic laser safety: remove all watches/jewelry to prevent unintentional reflection, wear appropriate safety glasses, and during laser operation ensure “Laser in Use” signs are posted at all entrances.
3. During installation of the laser, and further adjustments, use proper safety procedures to prevent a falling object injury.
4. Utilize the buddy system anytime work is to be done underneath the tunnel.

Appendix 2

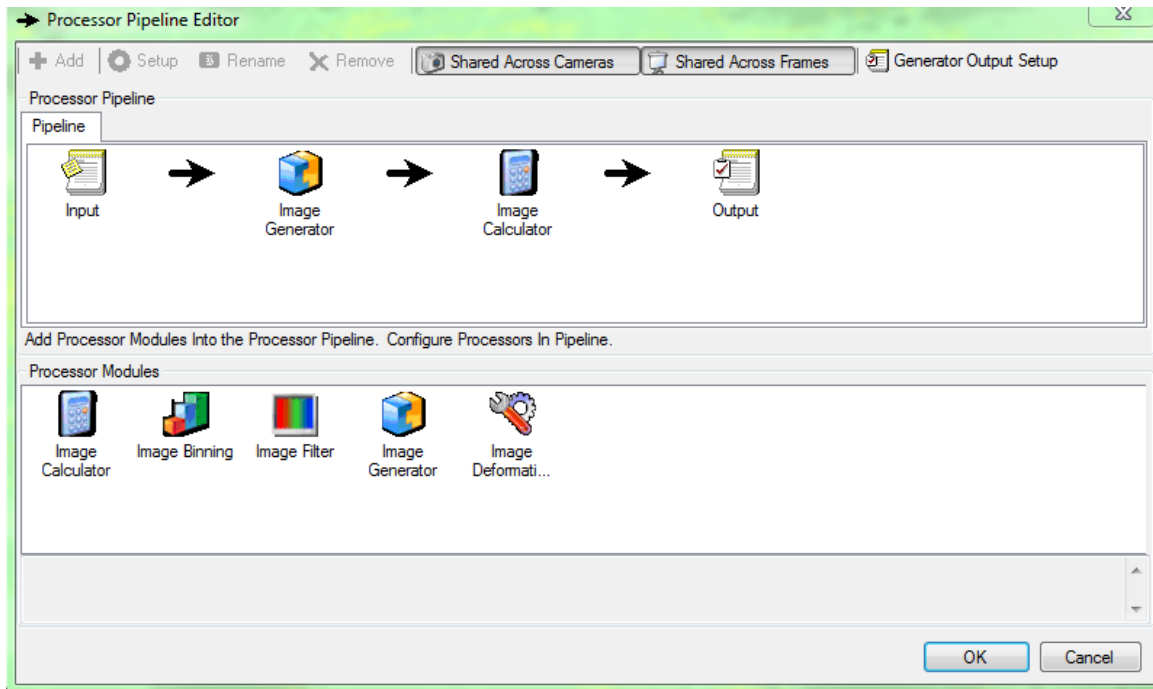
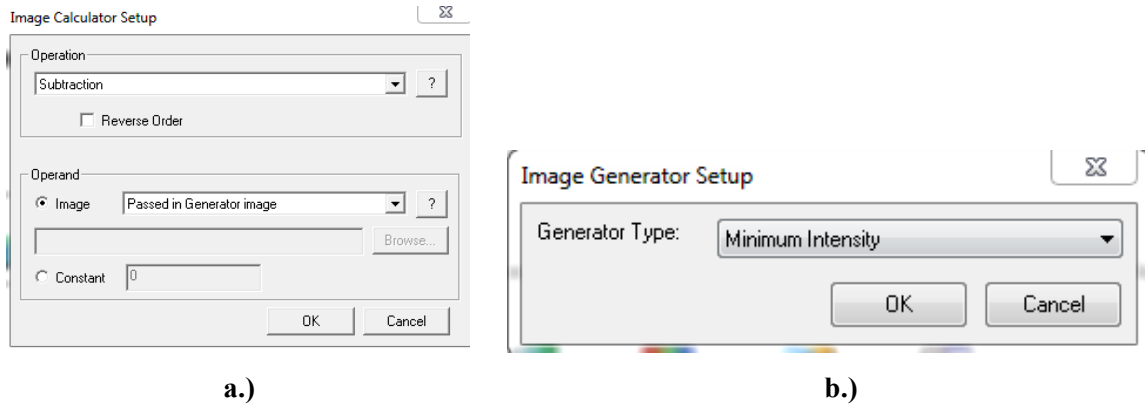


Figure 16. Pre-Processing Settings



a.)
b.)
Figure 17. a.) Image Calculator Setup. b.) Image Generator Setup

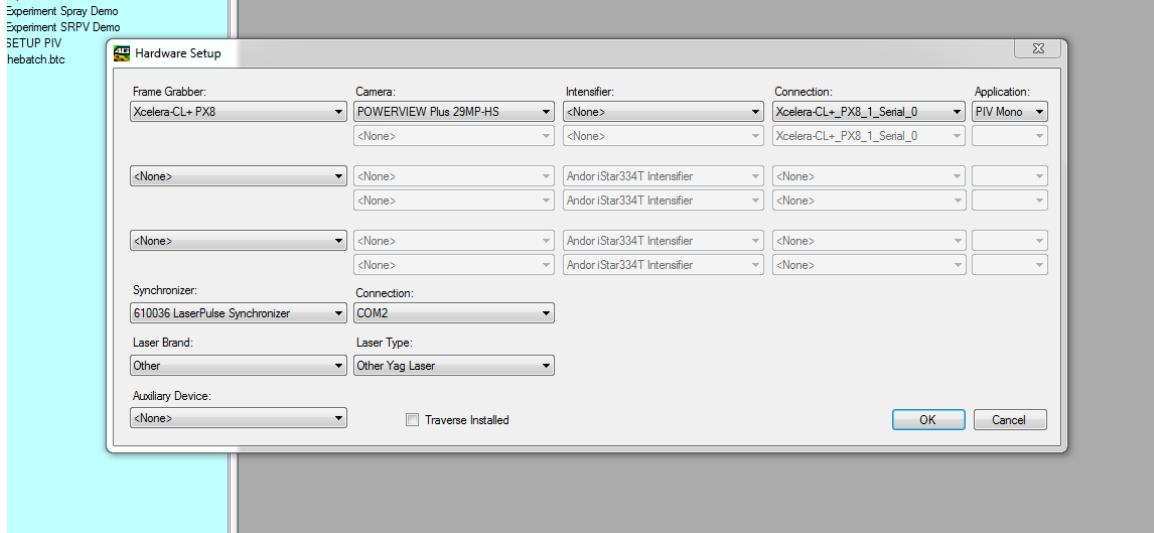


Figure 18. Hardware Settings in Insight 4G

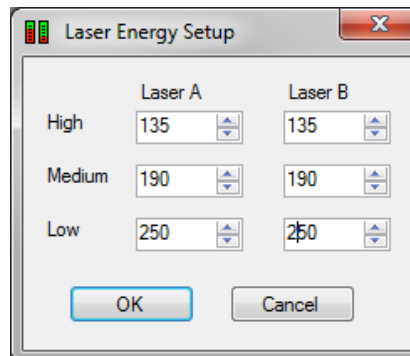


Figure 19. Default Laser Settings in Insight 4G

	U	V	Velocity Magnitude
Mean (Pixels/Delta T)	23.159483	-0.550641	23.166028
Standard Deviation (Pixels/Delta T)	1.435937	0.743340	1.616932
Turbulence Intensity	0.003844	0.004872	0.006206
Minimum (Pixels/Delta T)	18.299999	-2.698127	18.497834
Maximum (Pixels/Delta T)	26.131676	1.744564	26.189845
Mean (m/s)	0.271970	-0.006466	0.272046
Standard Deviation (m/s)	0.016963	0.008729	0.018988
Turbulence Intensity	0.003844	0.004872	0.006206
Minimum (m/s)	0.214903	-0.031685	0.217226
Maximum (m/s)	0.306873	0.020487	0.307556
Total Vector Count	110698		
Good Vector Count	107634		
Bad Vector Count	0		
Interpolated Vector Count	3064		
Good Vector Percent	97		
Bad Vector Percent	0		
Interpolated Vector Percent	3		

Figure 20. Vector Statistics Information Page

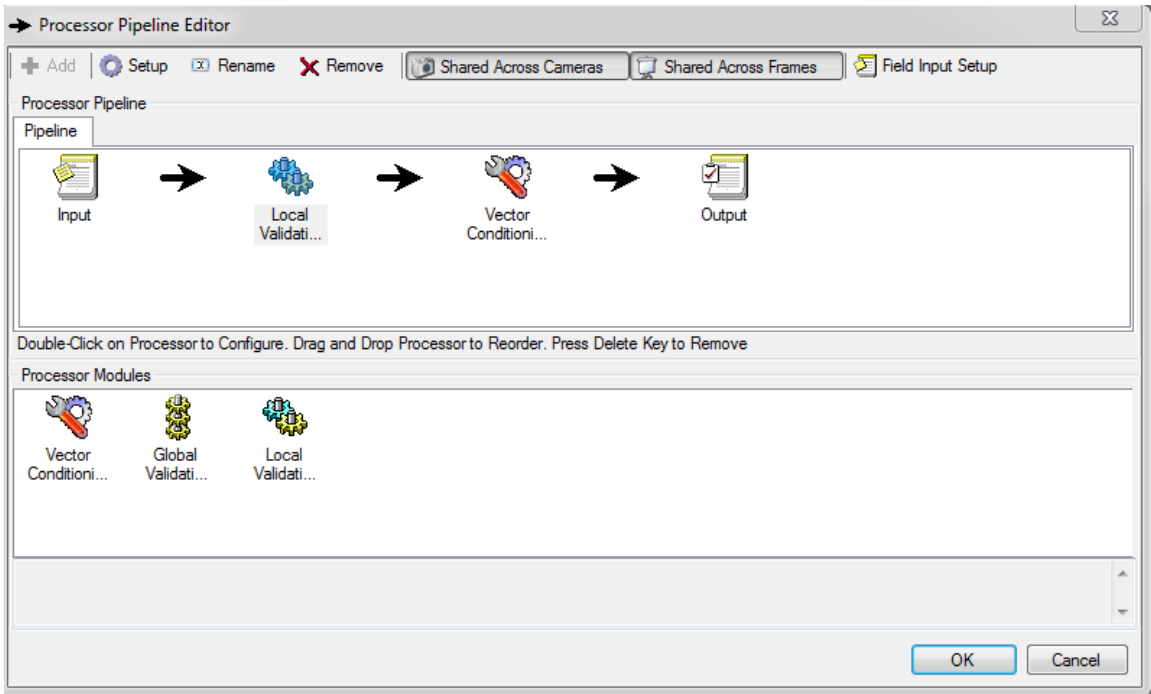


Figure 21. Post-Processing Setup

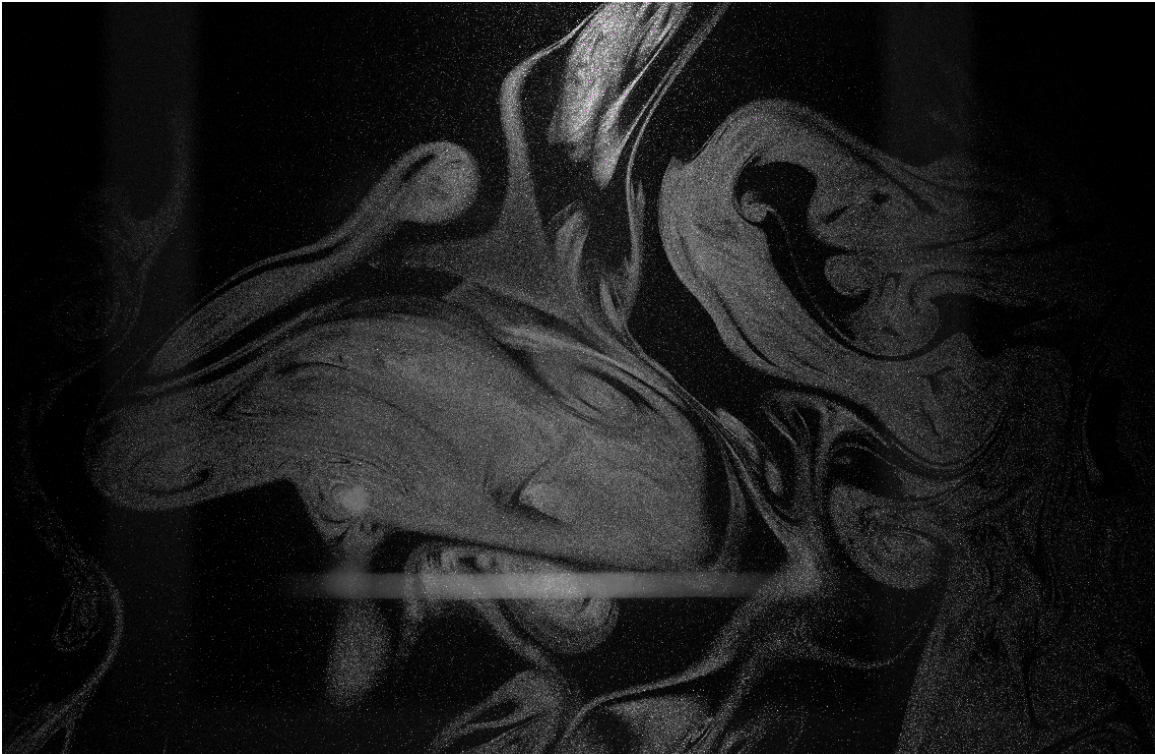


Figure 22. Image before Pre-Processing has occurred



Figure 23. Image Generated during Pre-Processing

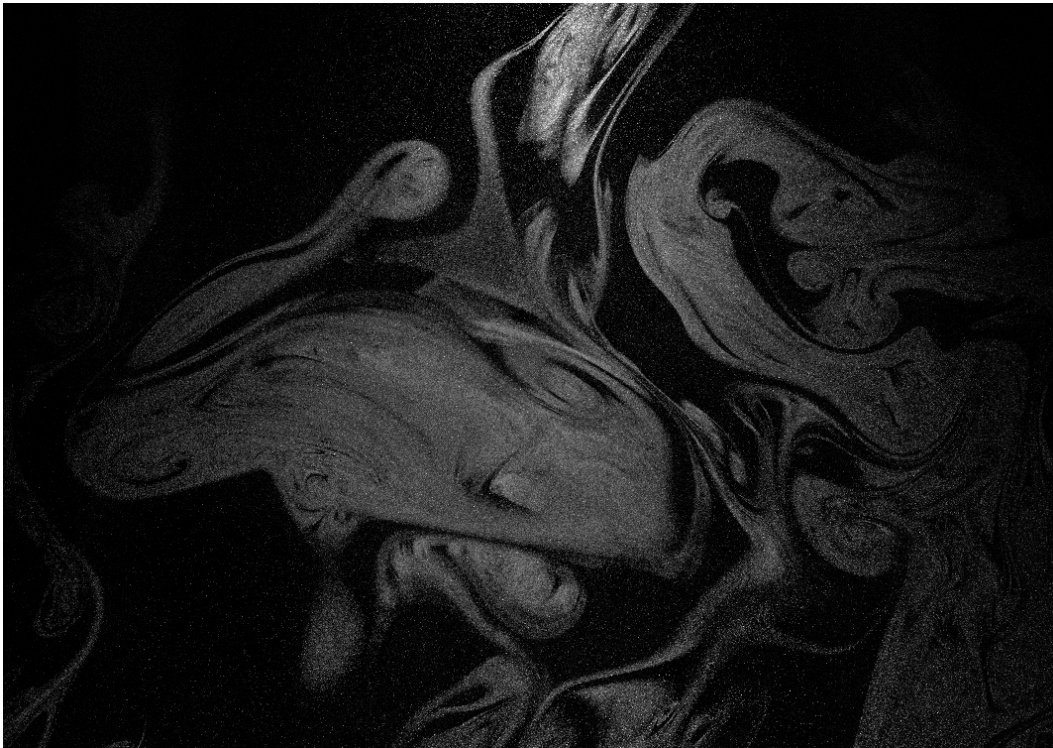


Figure 24. Image after Pre-Processing Generated Image has been removed



Figure 25. CONEX Tower 1:25 Model No Velocity Vectors Time 1



Figure 26. CONEX Tower 1:25 Model No Velocity Vectors Time 2

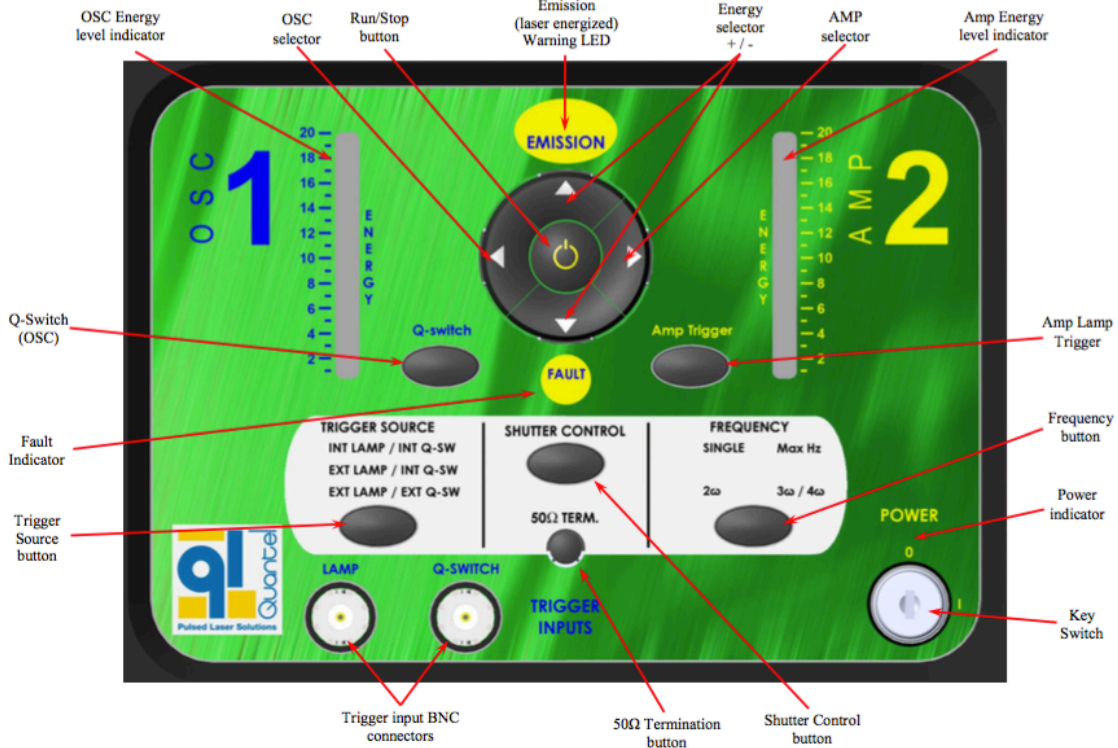


Figure 27. ICE Unit Front Control Panel [10]

Use the following procedures to drain the coolant from the ICE, the Laser Head and the coolant lines whenever:

- It is to be shipped.
- It will remain unused or stored for periods of time longer than six months.

Draining the ICE

1. Turn the Key Switch to OFF.
2. Have a container ready to hold the drained fluid.
3. Disconnect the red and blue coolant lines from the back of the ICE and the Laser Head. Drain the coolant from the lines into the container.
4. Remove the drain tube from its storage location inside the ICE back panel. Remove the protective cap from the drain tube.
5. Connect the drain tube to the blue connector on the ICE.
6. Remove the cap from the Coolant Reservoir.
7. Position the drain tube and container.
8. Turn the Key Switch to ON.
9. Press and hold the Pump Control switch to pump the fluid out through the drain tube. Continue for 30 seconds after fluid stops exiting the tube.
10. Disconnect the drain tube and insert it into the red connector on the ICE.
11. Drain coolant from the red return side of the coolant system using gravity flow only. Do NOT blow into the reservoir.
12. Disconnect the drain tube and reinstall its protective cap. Return the drain tube to its storage location.
13. Turn the Key Switch to OFF.



Figure 28. Draining Procedure [10]

CAUTION: Before proceeding, switch the Key Switches to the OFF position. Switch OFF the AC Mains Power and unplug the AC power cords.

The DI Cartridges must be replaced every six months. Use the following procedure to change the cartridge:

1. Disconnect the blue coolant line from the back of the ICE and the Laser Head. Drain the coolant from the blue line into an appropriate container.
2. Locate the DI Cartridge. Note the flow arrow direction before removing.
3. Press the gray collet against the tan body fitting of the DI cartridge in the direction shown with orange arrows. Firmly hold the collet in this position while pulling on the coolant line in the direction shown with the green arrow to remove the cartridge.

CAUTION: Failure to follow this process causes the collet teeth to damage the surface of the O-ring of the internal coolant line fitting.

4. Orient the new cartridge flow arrow in the correct direction (away from the ICE). Then one at a time, push the tube stems into the cartridge fittings, until the tube stem presses fully against the internal stop.
5. Test the cartridge installation by attempting to pull the coolant lines out of the cartridge. Ensure that the tube stem is fully inserted before continuing to the next step.
6. Reconnect the blue coolant line to the back of the ICE and Laser Head.
7. Add distilled water to the reservoir to refill it.

Note:

The DI Cartridge Kit is part number 88800053 should there be need to order replacements.

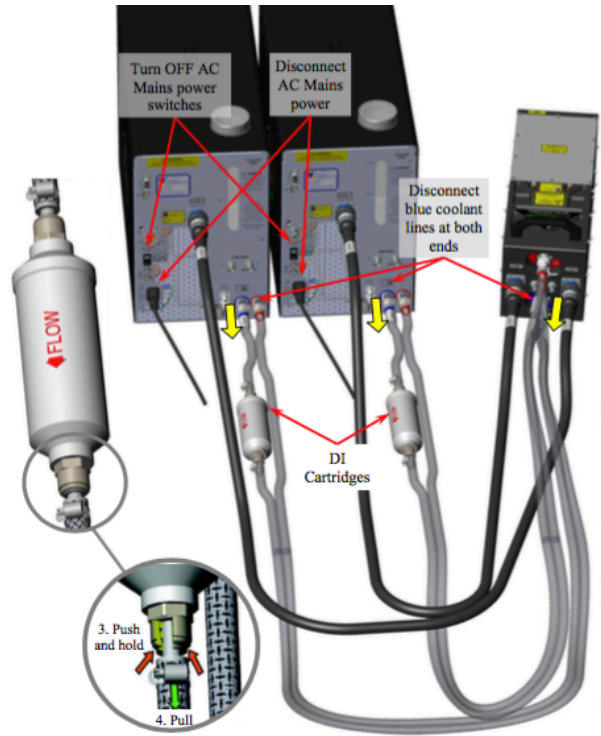


Figure 29. Changing the Deionization Filters [10]