Analysis and Design of the Federal Aviation Administration Fire Test Burner

Particle Image Velocimetry Applied to Fire Safety Research

Presented to: International Aircraft Materials Fire Test Working Group – Naples, FL, USA

By: Robert Ian Ochs

Date: Wednesday, March 4, 2009

Outline

- **Explanation of PIV**
  - Fundamental Principles
  - Measurement Methods
  - FAA PIV Lab
- **Acquired Data**
  - Results
  - Analysis
- **Summary and Future Work**

Motivation

- **The FAA utilizes a modified oil burner to simulate the effects of a post-crash fuel fire on an aircraft fuselage and interior components**
  - The specified burner is a typical home heating oil burner
  - Burner uses JP8 or Jet A jet fuel
- **Burner flame characteristics scaled directly from measurements made from full scale pool fire testing**
  - Heat flux
  - Temperature
  - Material burn-through times
- **The burner is used to measure the fire worthiness of aircraft materials**
  - Seats, thermal-acoustic insulation, and cargo liners

Objectives

- **Identify key parameters**
  - Burner operation is known to be dependent upon many factors
  - All relevant factors must be identified and ranked in order of their impact on burner performance
    - Fuel spray
    - Air flow
    - Burner geometry
    - External effects
    - etc, etc, etc…
- **Improve design**
  - Burner is no longer manufactured or available for purchase
  - An equivalent burner must be made available to industry for certifying materials and designs
  - The overall performance, repeatability, and reproducibility of the burner should be improved
  - The burner should be specified such that it can be easily manufactured from readily available materials
  - Optimization of the burner by manipulating the key parameters to provide for an overall better burner design

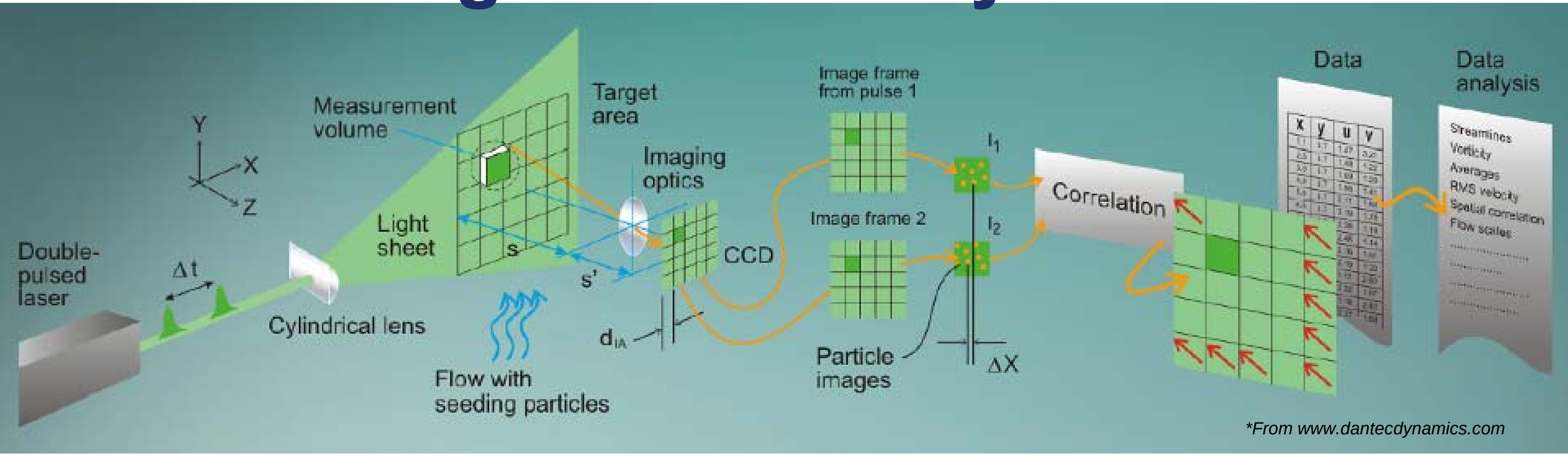
Methodology

- **Utilize flow measurement techniques to study the operation of the burner and assess each component or parameter**

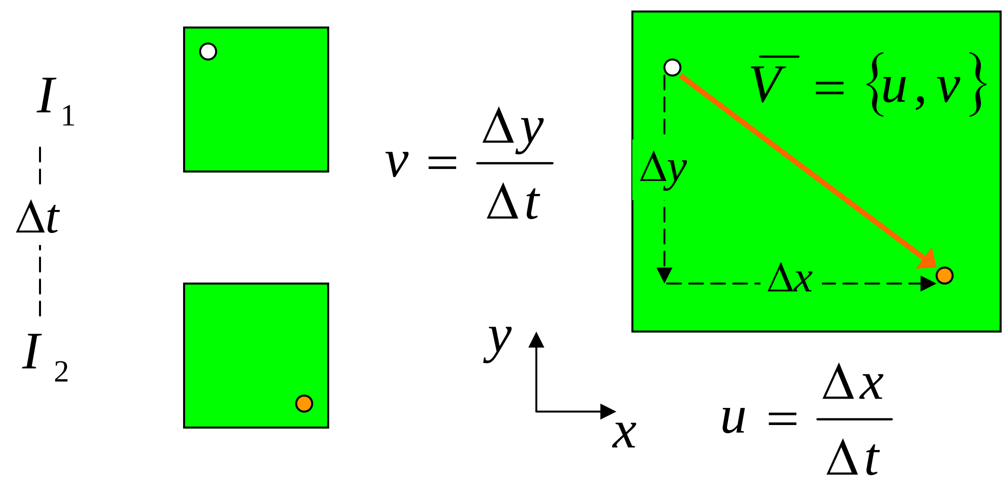
- **Selection of a technique:**
  - Hot Wire Anemometry
  - Laser Doppler Anemometry
  - Particle Image Velocimetry

- **PIV was chosen as the most robust method for this study**
  - Instantaneous, non-intrusive, planar velocity measurements in 2-D with capabilities for 3-D
  - Hot and cold flows (reacting and non-reacting)
  - Capabilities for particle sizing (spray characterization)

Particle Image Velocimetry



- **Particle Image Velocimetry (PIV) is a whole-flow-field visualization technique that provides instantaneous velocity vector measurements in a cross-section of a flow**



PIV for Fire Safety

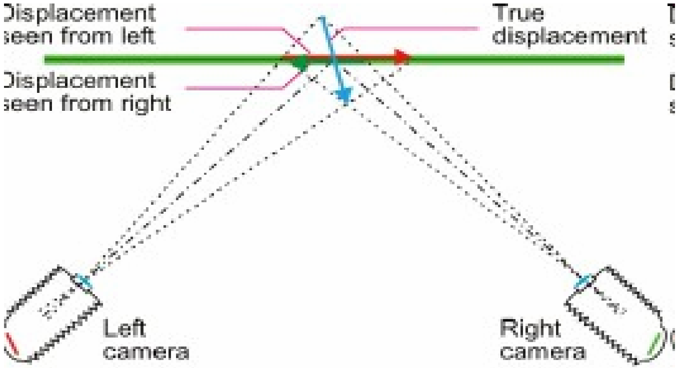
- **Material fire test methods dependent upon accuracy of test methods**
  - Fire test methods involve burners
    - Burners are driven by fluid-thermal processes
    - Test results are completely dependent upon these processes
    - Insight into the fundamental burner parameters will lead to optimization of these parameters
    - Optimization leads to increased level of accuracy and increased confidence in the burner's repeatability and reproducibility
    - With modern materials processing technology and increased levels of industrial quality control, a more clearly defined level of failure is desired so that manufacturers can design to a specific level of safety
  - Analysis of post-crash fuel fires
    - Visualization of the flow field created by a pool fire
    - Analysis of flame impingement on a fuselage
- **Other uses**
  - Visualization of fluid flow within an enclosure
    - Smoke spread from a fire in a cargo compartment or cabin
    - Extinguishment agent propagation for fire suppression
    - Nitrogen dispersion in a partitioned fuel tank or in cabin
  - Sprays
    - Water mist
    - Extinguishment agent sprays

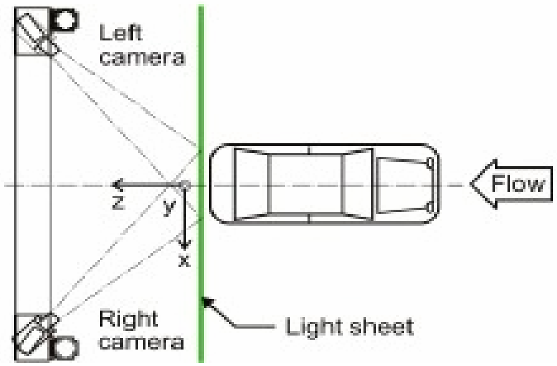
Fire Safety's PIV Laboratory

- **Dantec Dynamics 3D PIV system**
  - 2 FlowSense 2M cameras
  - SOLO PIV 120XT laser
  - PC with Dynamic Studio software for analyzing PIV images
  - Scheimpflug Camera Mounts
  - Beam Splitter
- **Current status**
  - Laboratory is on-line
- **Planned activities**
  - Analysis of oil burner
    - Nozzle spray
      - Identify key features of nozzle flow
      - Volume mapping of a nozzle spray, identify symmetry or asymmetry
      - Compare nozzles of same type and of different type
      - Determine optimal nozzle type, manufacturer, or seek to develop a new nozzle
    - Air flow
      - Visualization of the burner exit flow field in different planes
      - Identify the parameters that lead to a more uniform flow field
    - Combined air and fuel flow
      - Determine optimal setting for air-fuel droplet mixing
    - Analysis of flame
      - Determine if flame is seeded with enough soot particles for good PIV measurements
      - Measure flame velocity field and determine if optimal burner settings lead to optimal flame

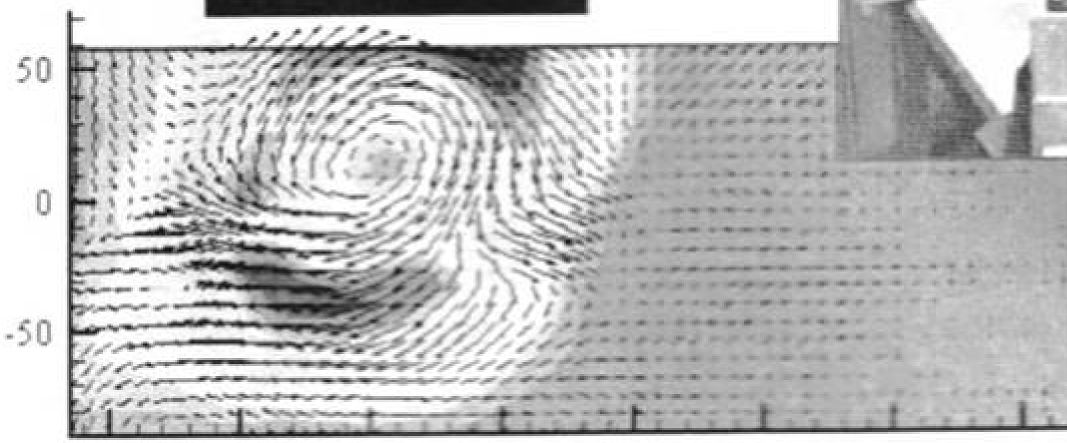
Stereoscopic 3D PIV

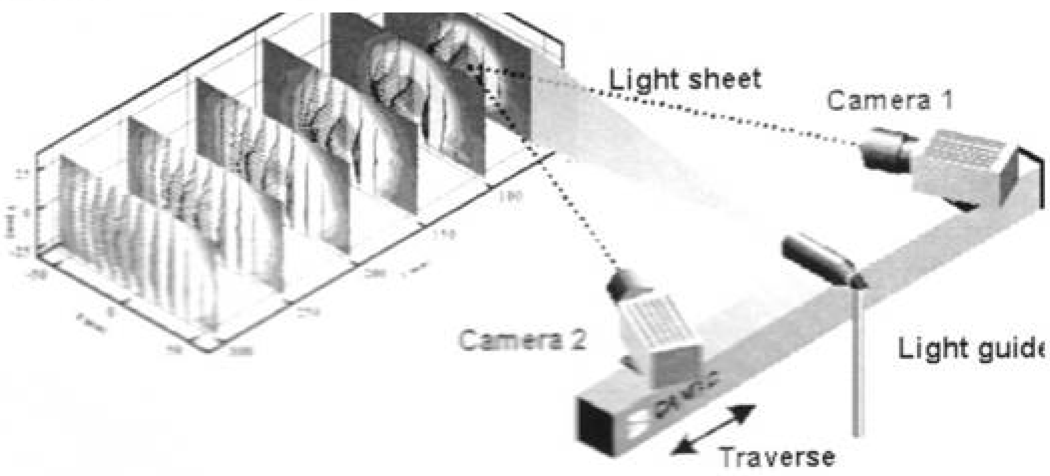
- Based on same fundamental principle as human eyesight
  - “When we look at a given object, our left and right eyes see two similar but not identical images. The brain compares the two images and interprets the slight variations to rebuild the three dimensional information of the object observed.”
    - 2 cameras → 2 eyes
    - Computer and software → brain
- We use this technique to obtain the out-of-plane velocity component (z)
- This is used to fully characterize the flow in a plane, and can give information on the swirl of the flow





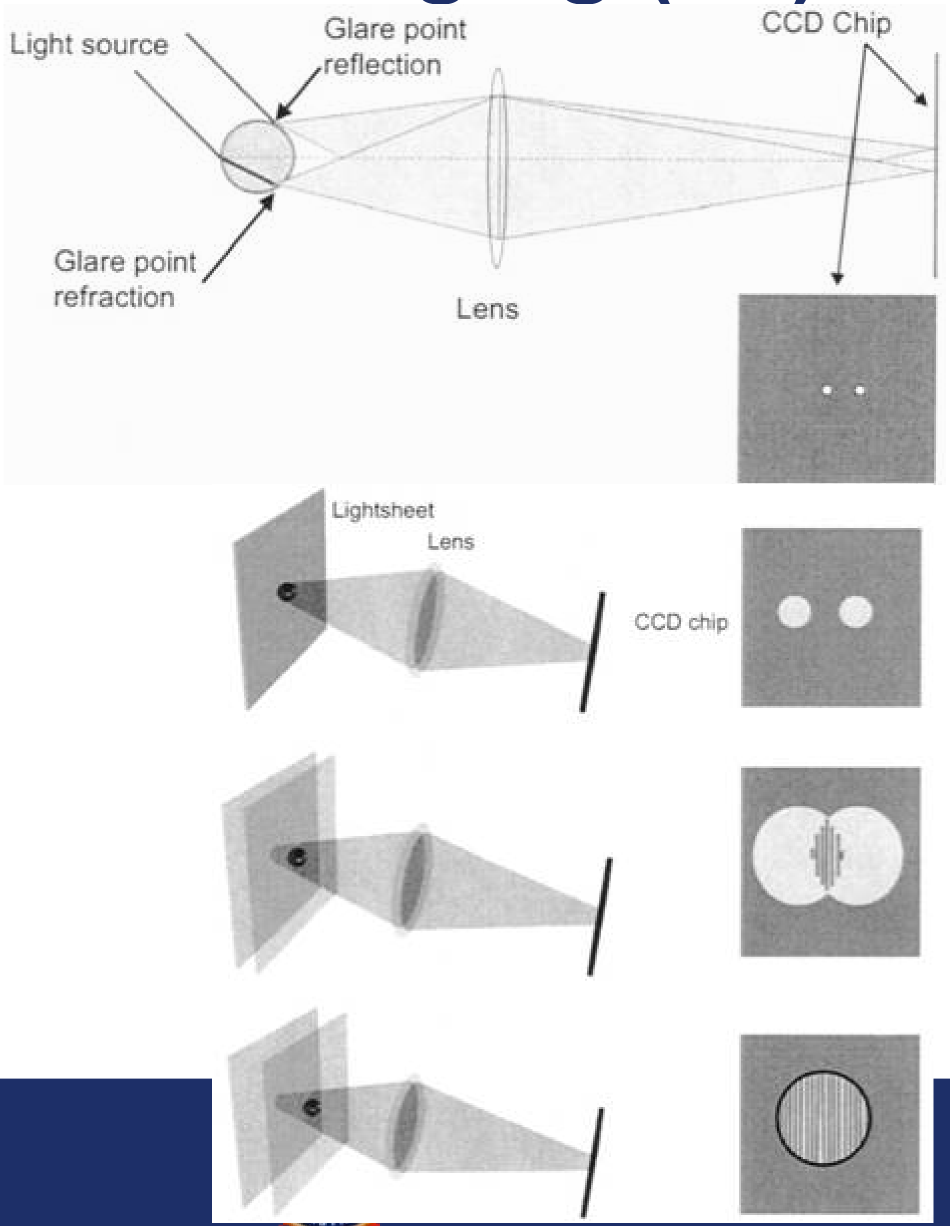
Stereoscopic 3D PIV



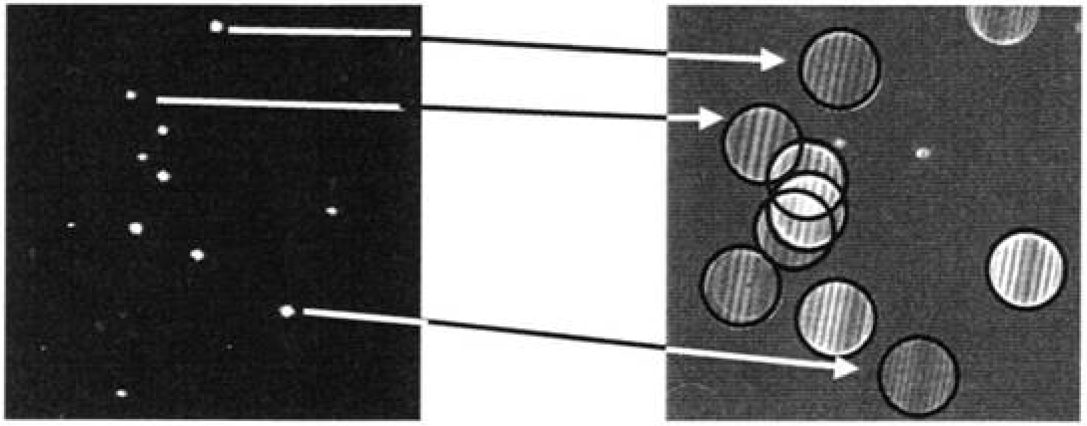


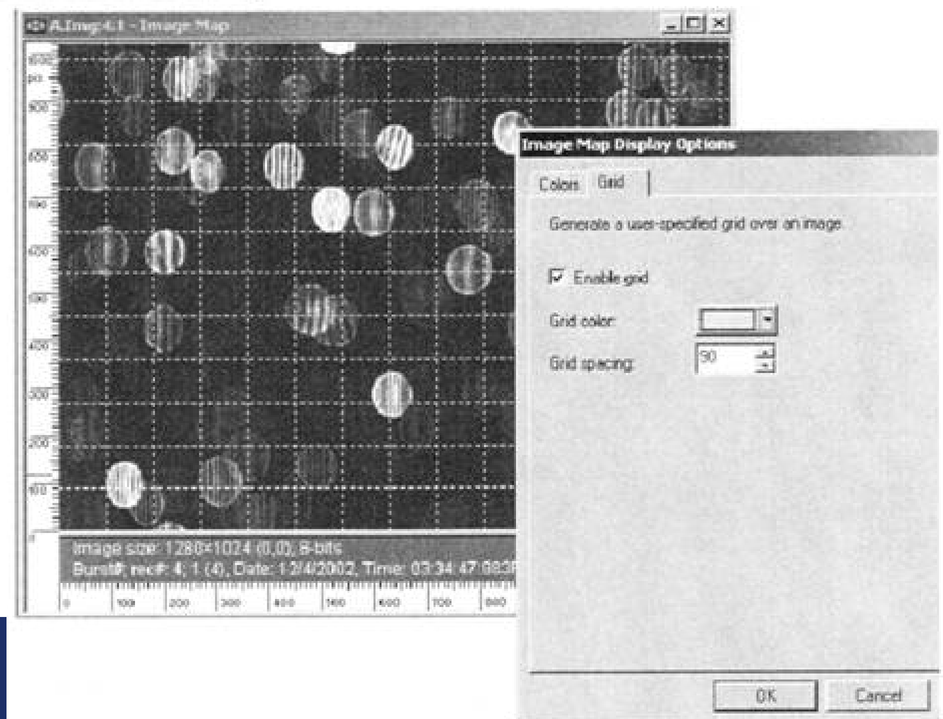
Interferometric Particle Imaging (IPI)

- Based on the interference of the relection and refraction glare points from an illuminated transparent particle
- 2 cameras see the same image, one is focused, the other defocused
- As the degree of defocusing increases, the two glare points merge into one single unified image with interference fringes
- It is possible to determine the distance between the glare points, or the size of the particle, from the frequency of the interference fringes in the defocused image.



Interferometric Particle Imaging (IPI)

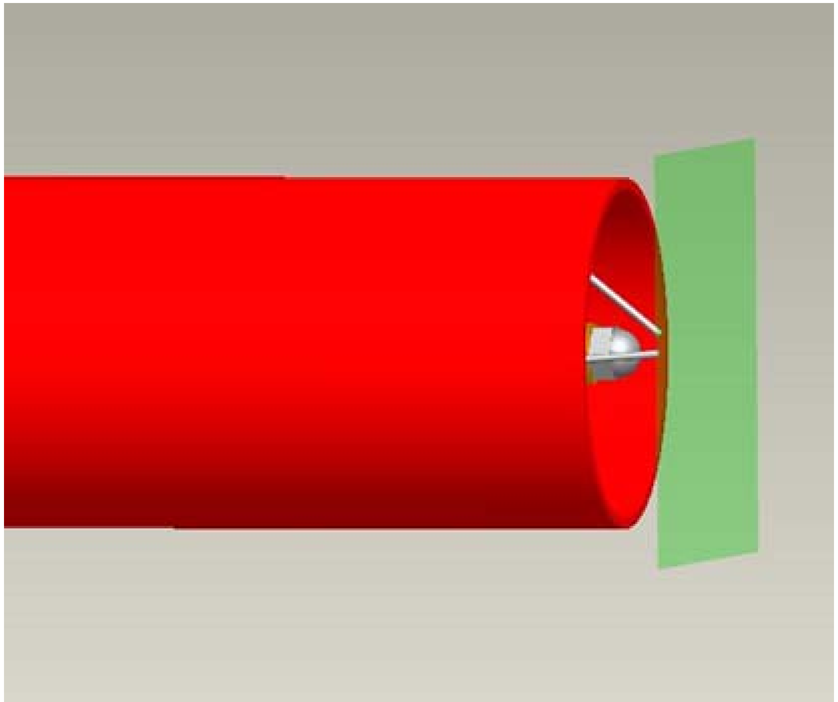




Recently Acquired Data

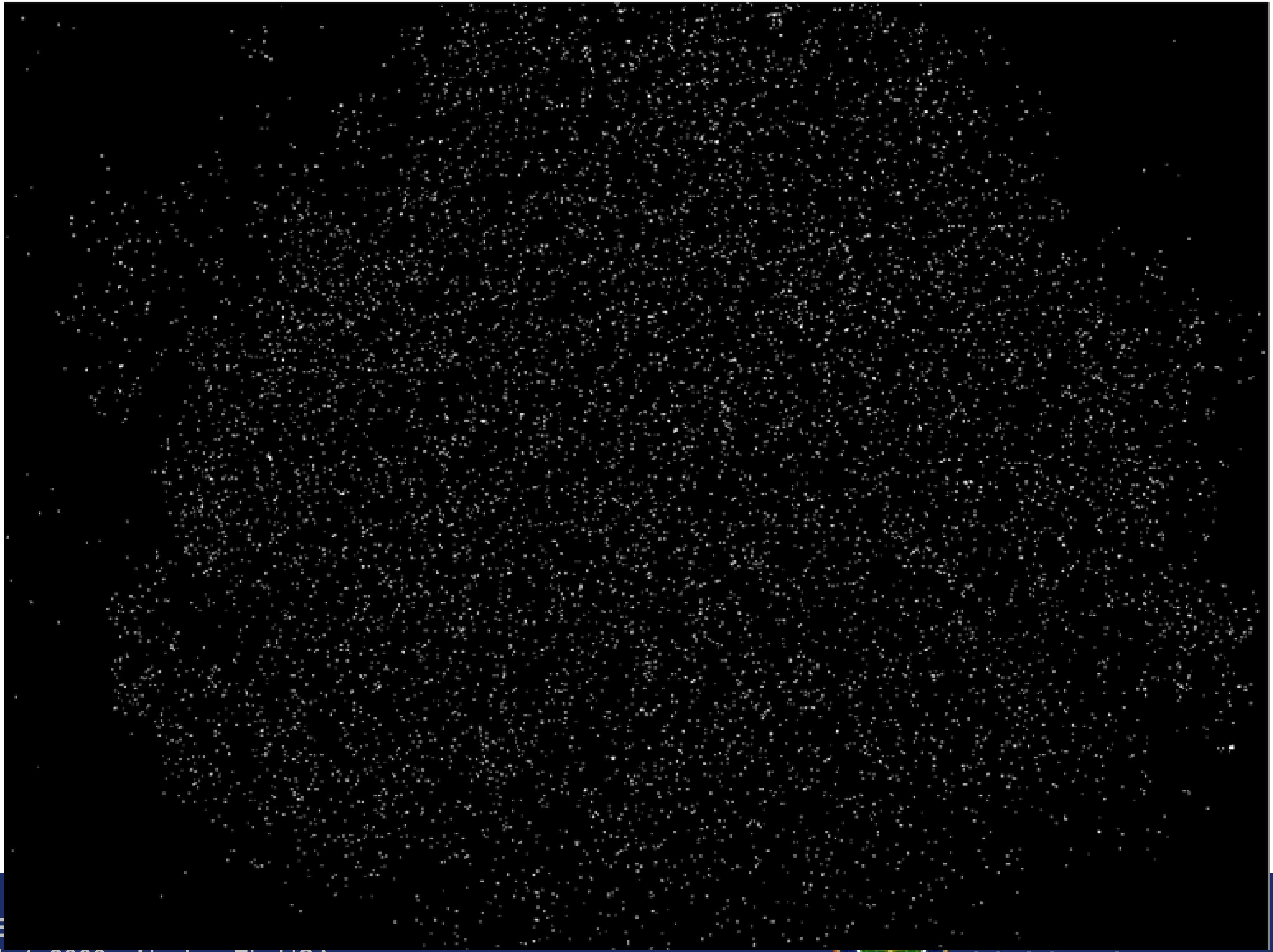
Burner Air Flow

Exit Air Flow from Draft Tube (Turbulator Removed)

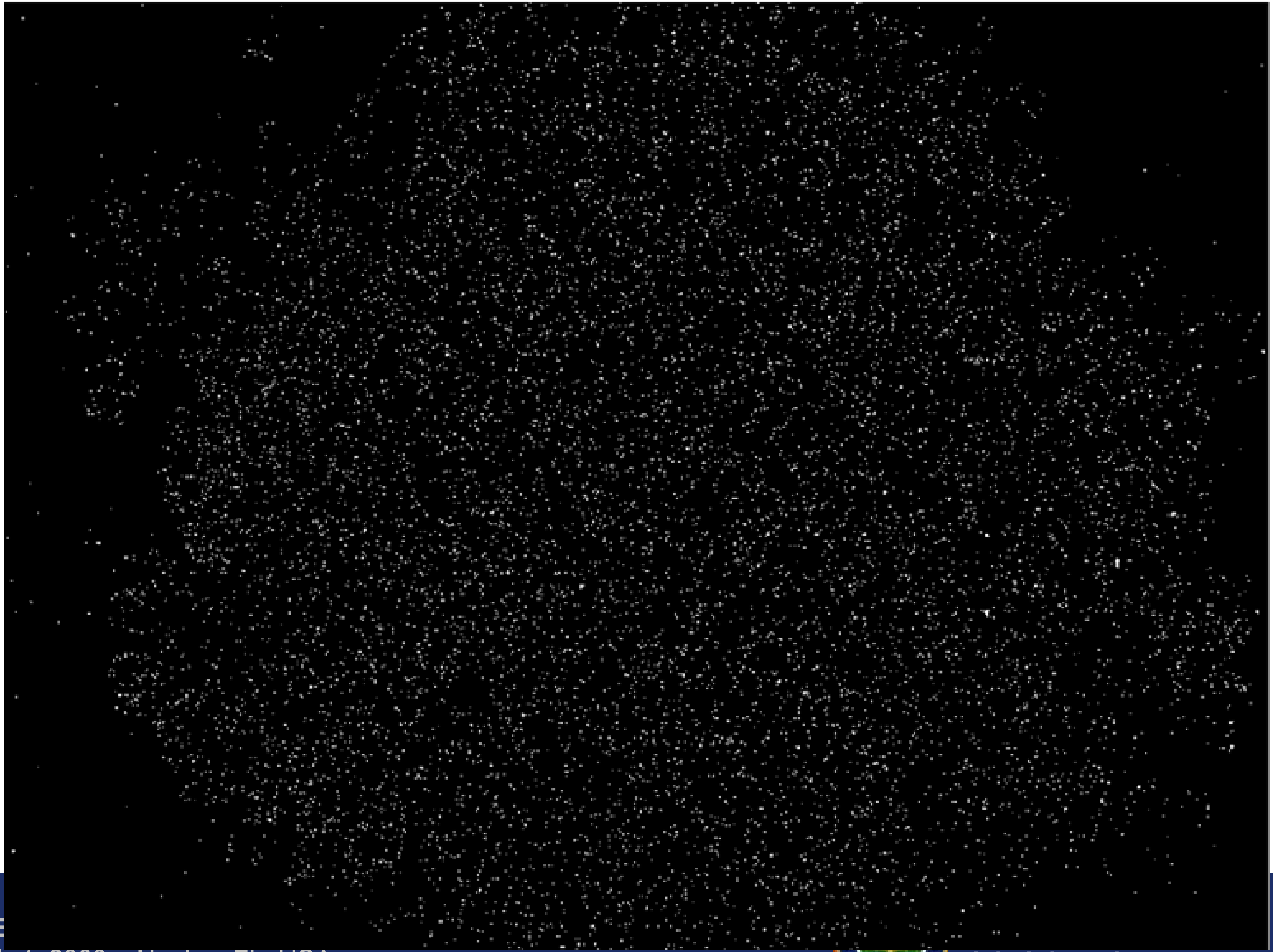


- Measurement plane is 1” from draft tube exit plane
- Flow is seeded with Aluminum Dioxide particles, ~15 micron
- Δt=100μs

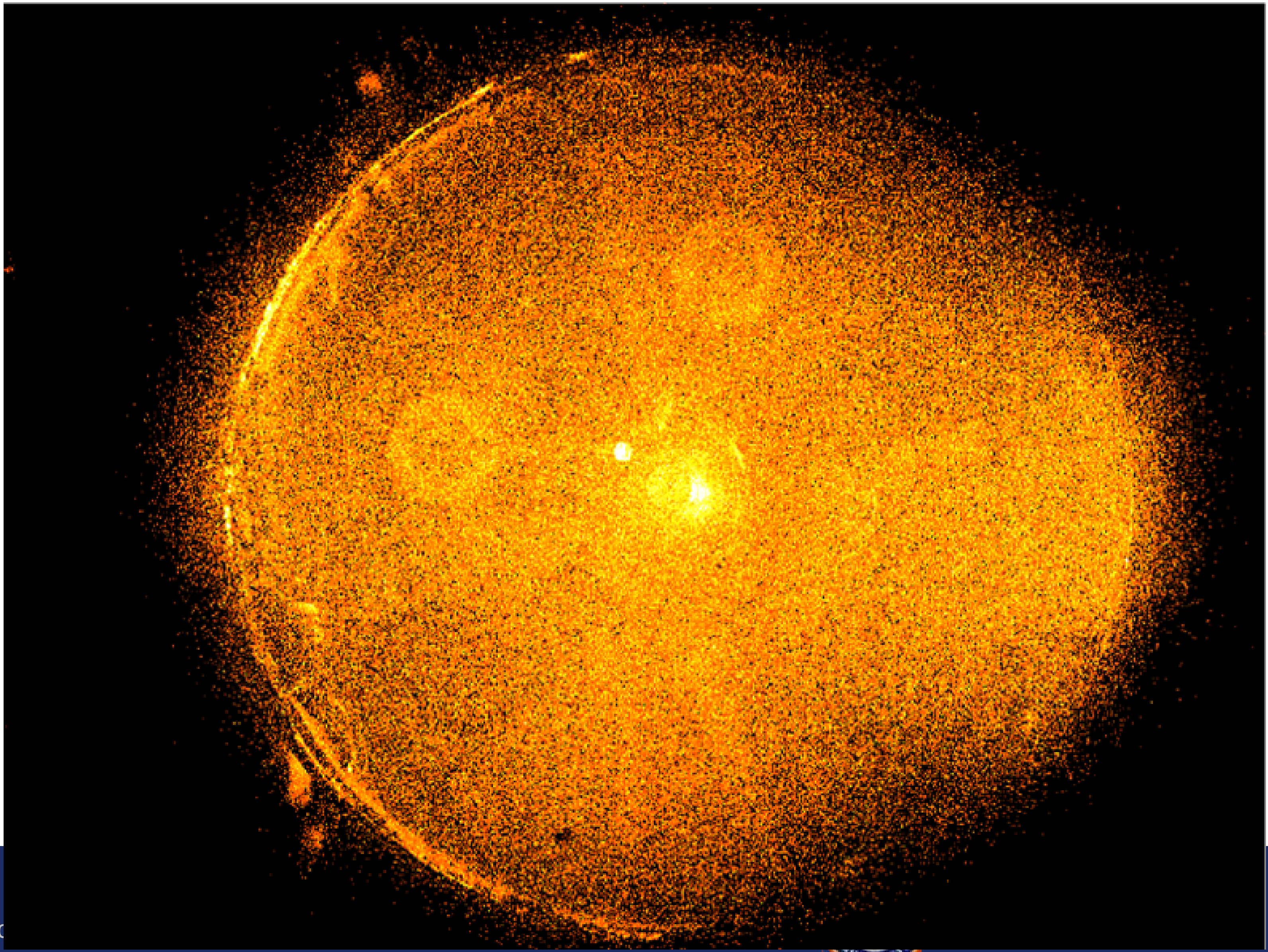
Raw Data Frame 1, t=0



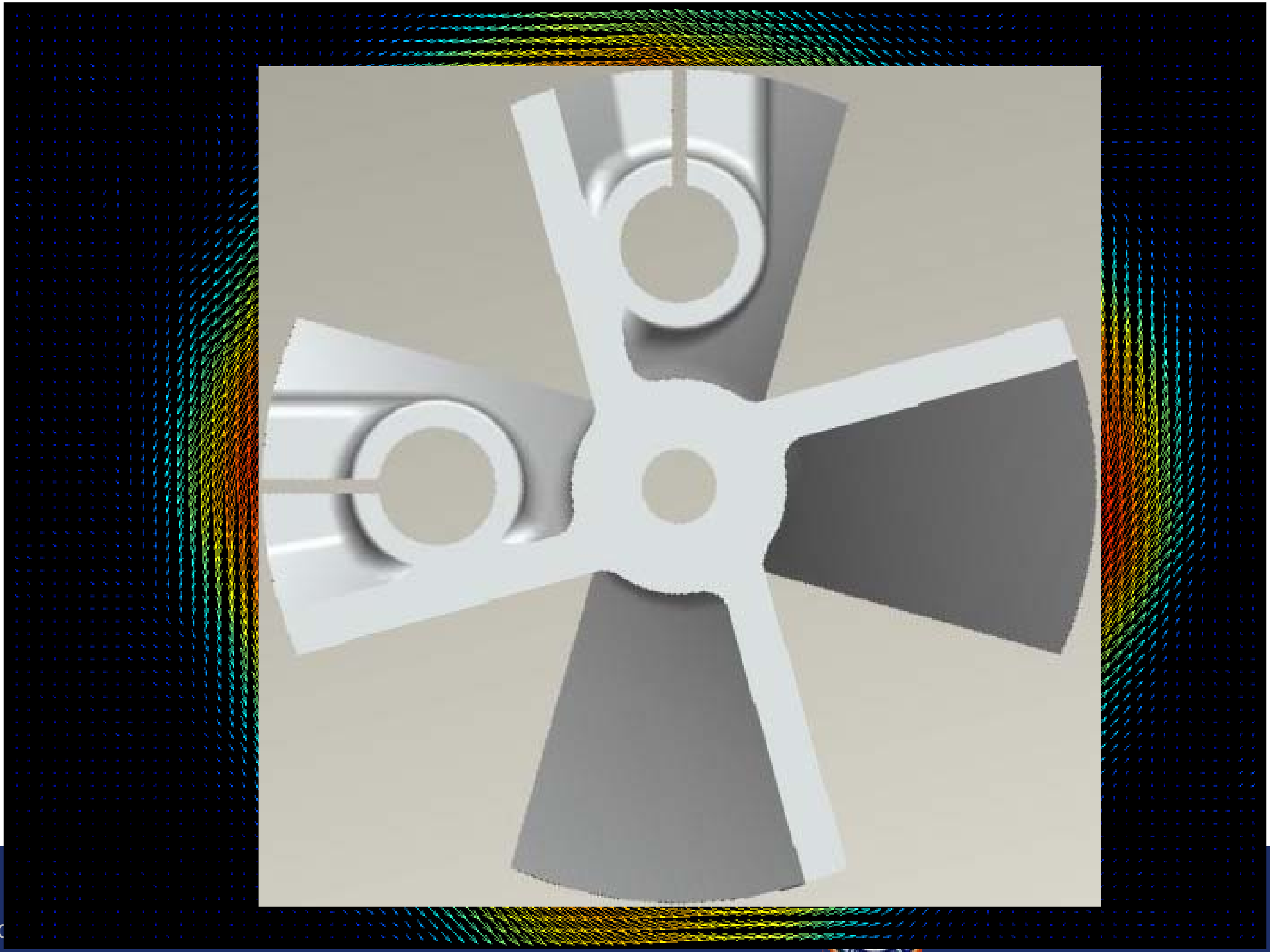
Raw Data Frame 2, t=100μs



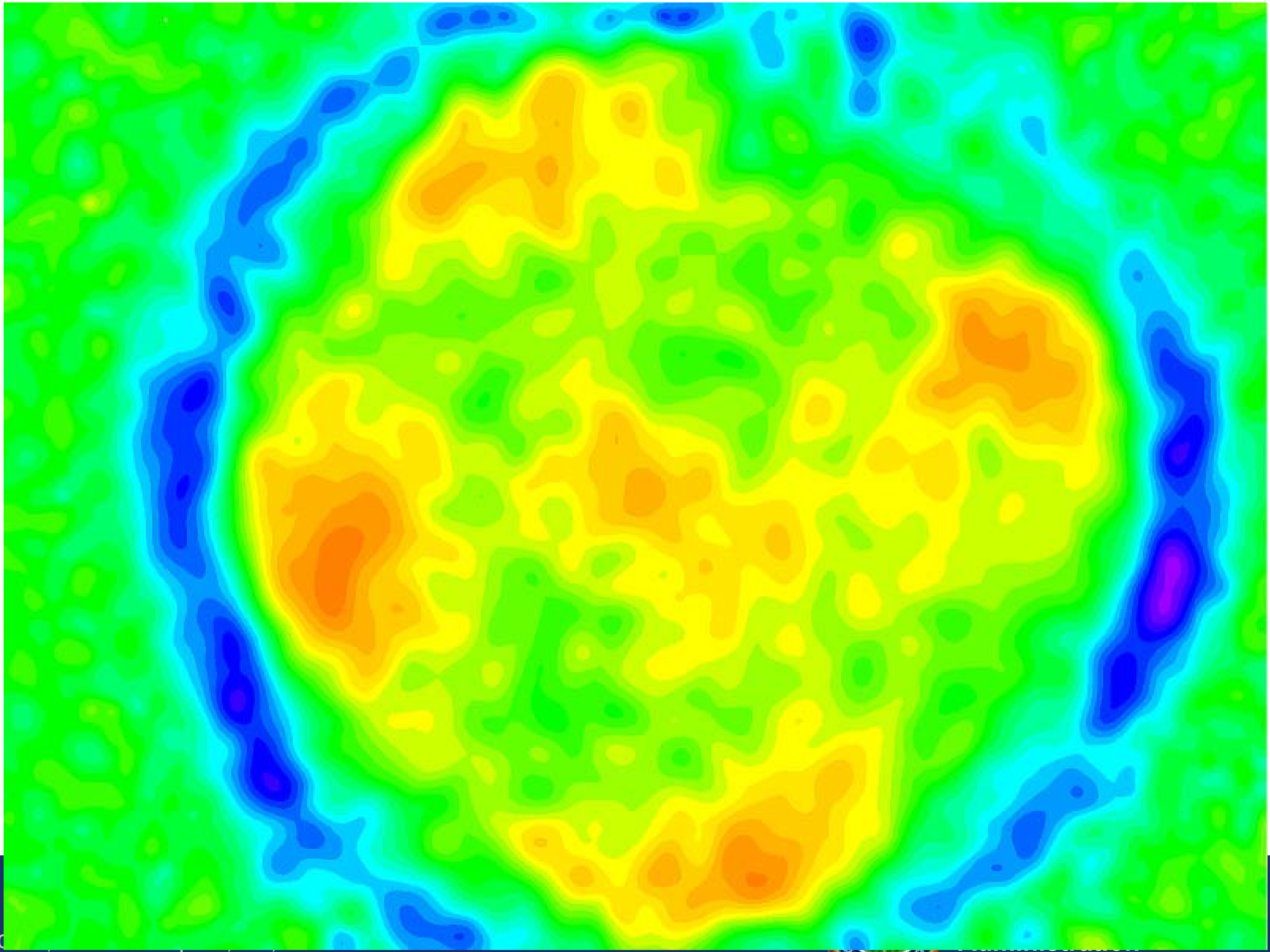
Mean Image – False Color



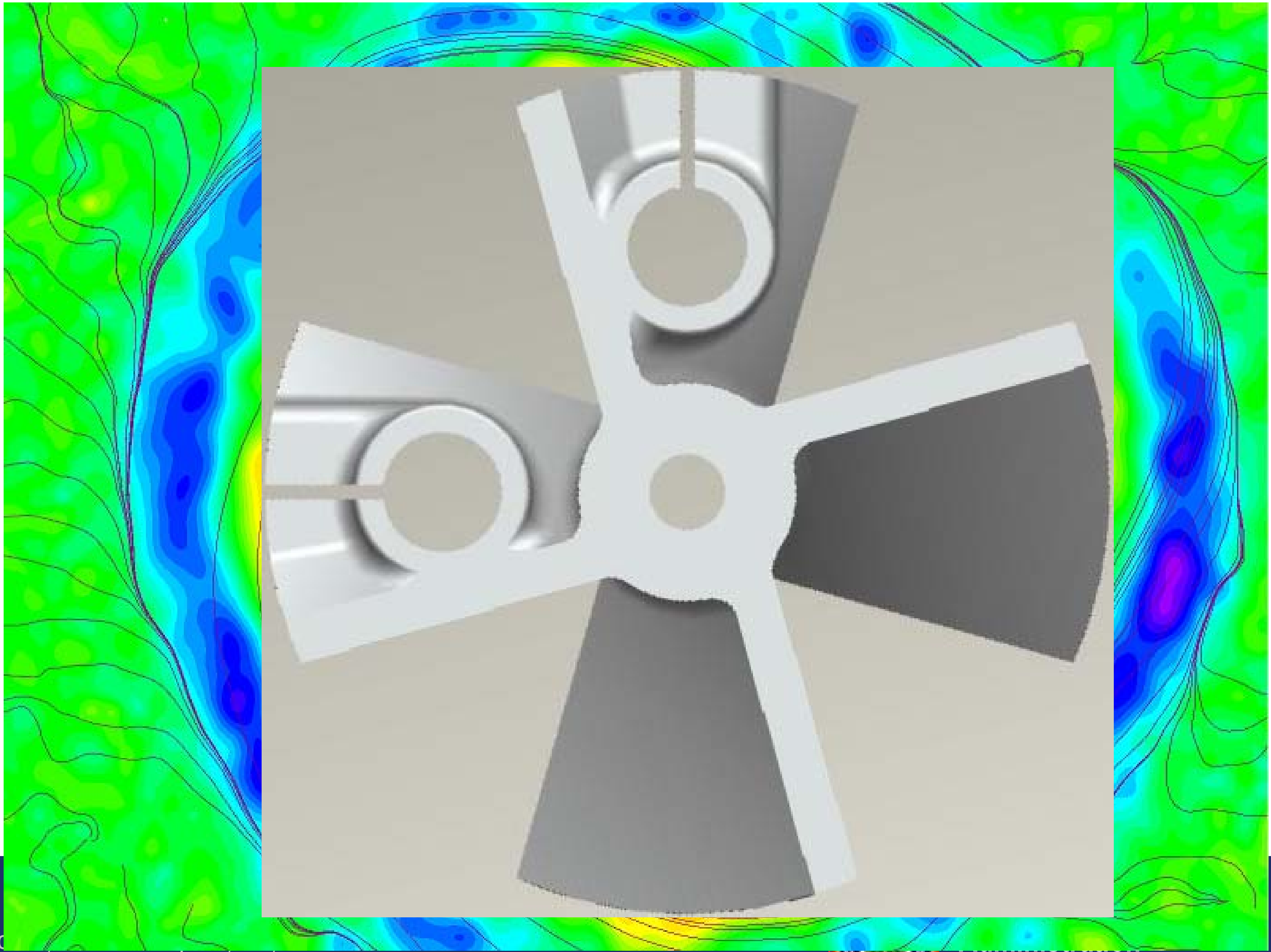
Vector Plot, range 0-4 m/s



Vorticity Field



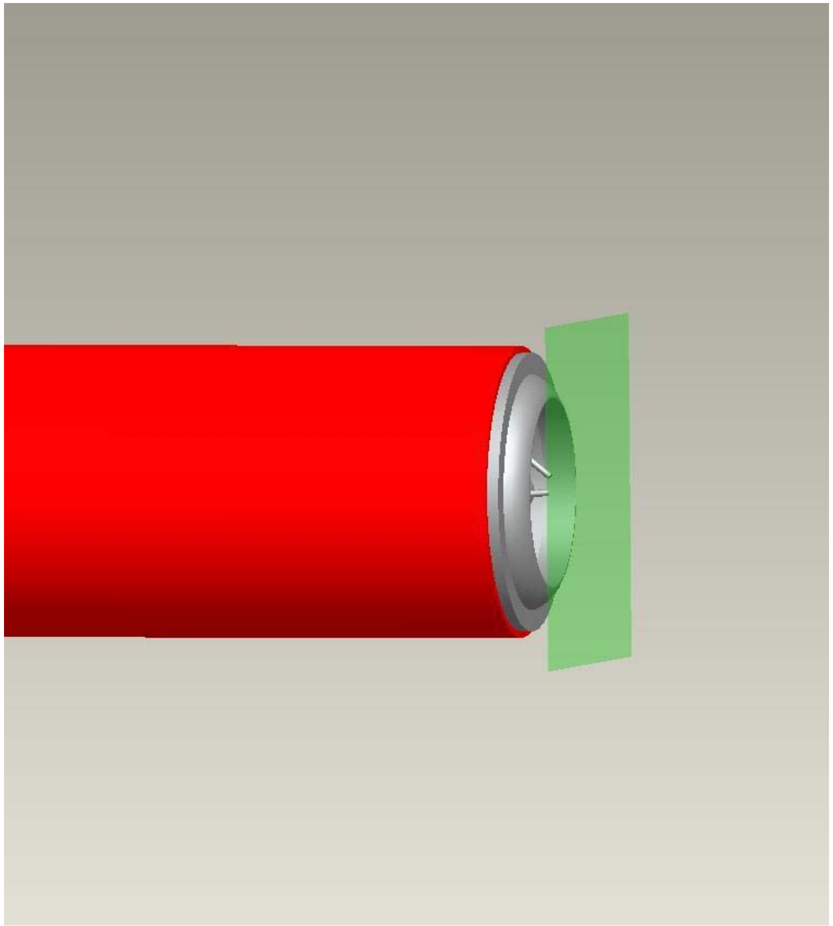
Vorticity and Streamlines



Analysis

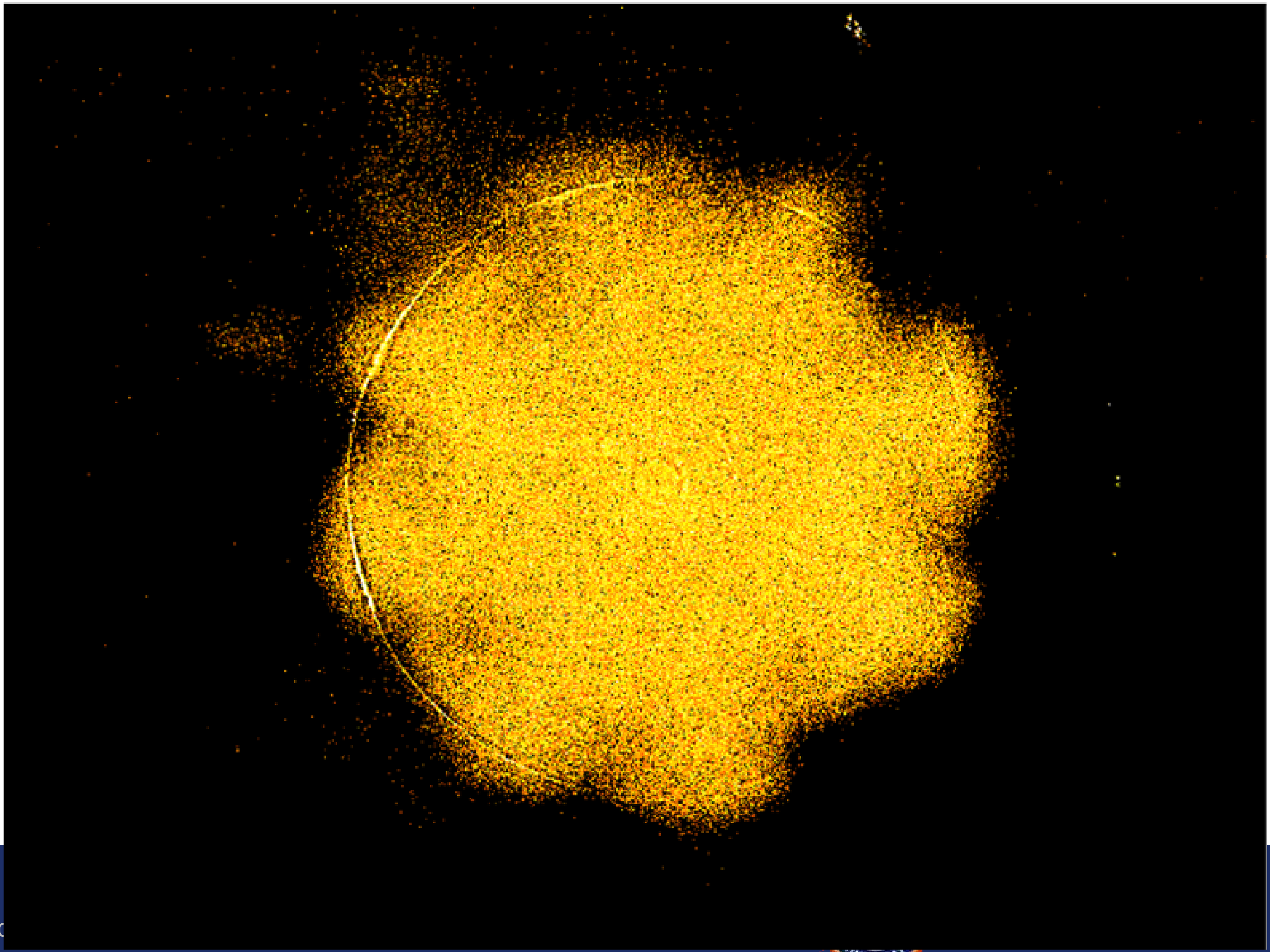
- The effect of the stator is apparent in the measured flow field
- Stator vanes appear to accelerate the flow and impart swirling motion
- Counterclockwise (positive) vorticity is seen in the center of the flow field, while clockwise (negative) vorticity is seen on the periphery of the flow

Exit Air Flow from Turbulator

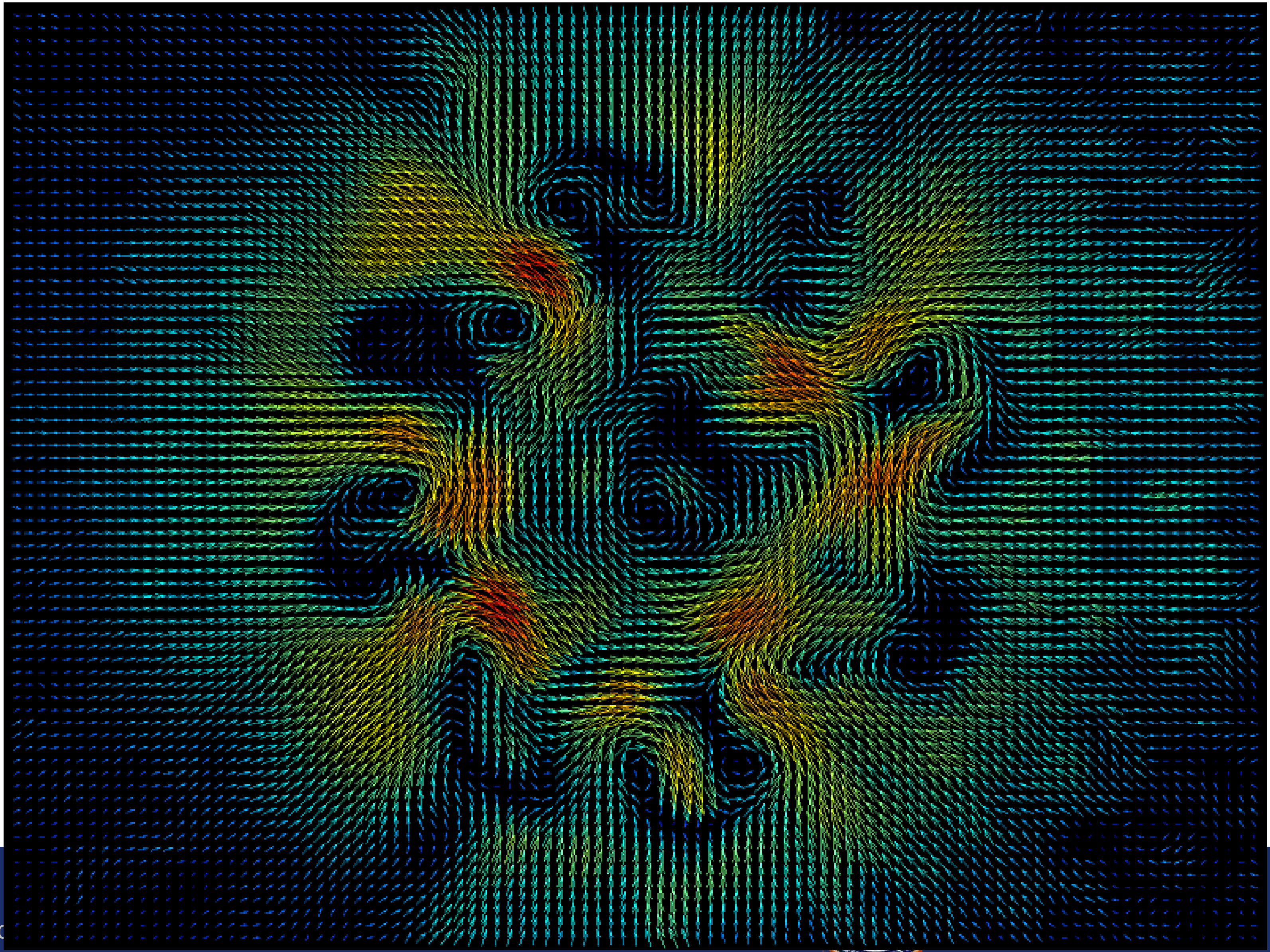


- Measurement Plane is parallel to the turbulator exit plane, ½" from exit
- Flow is seeded with Aluminum Dioxide particles, 15 micron
- $\Delta t = 100 \mu s$

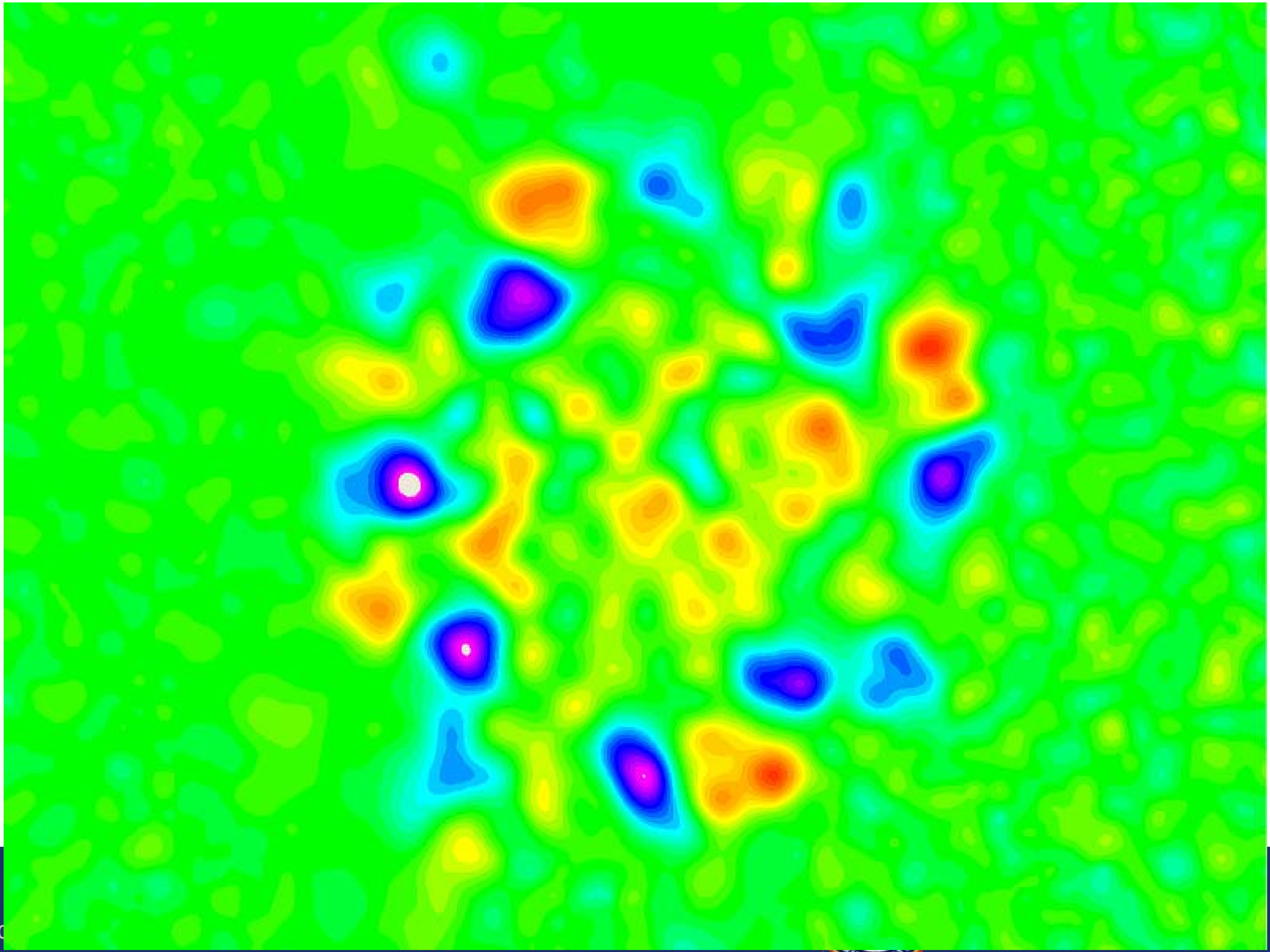
Mean Image – False Color



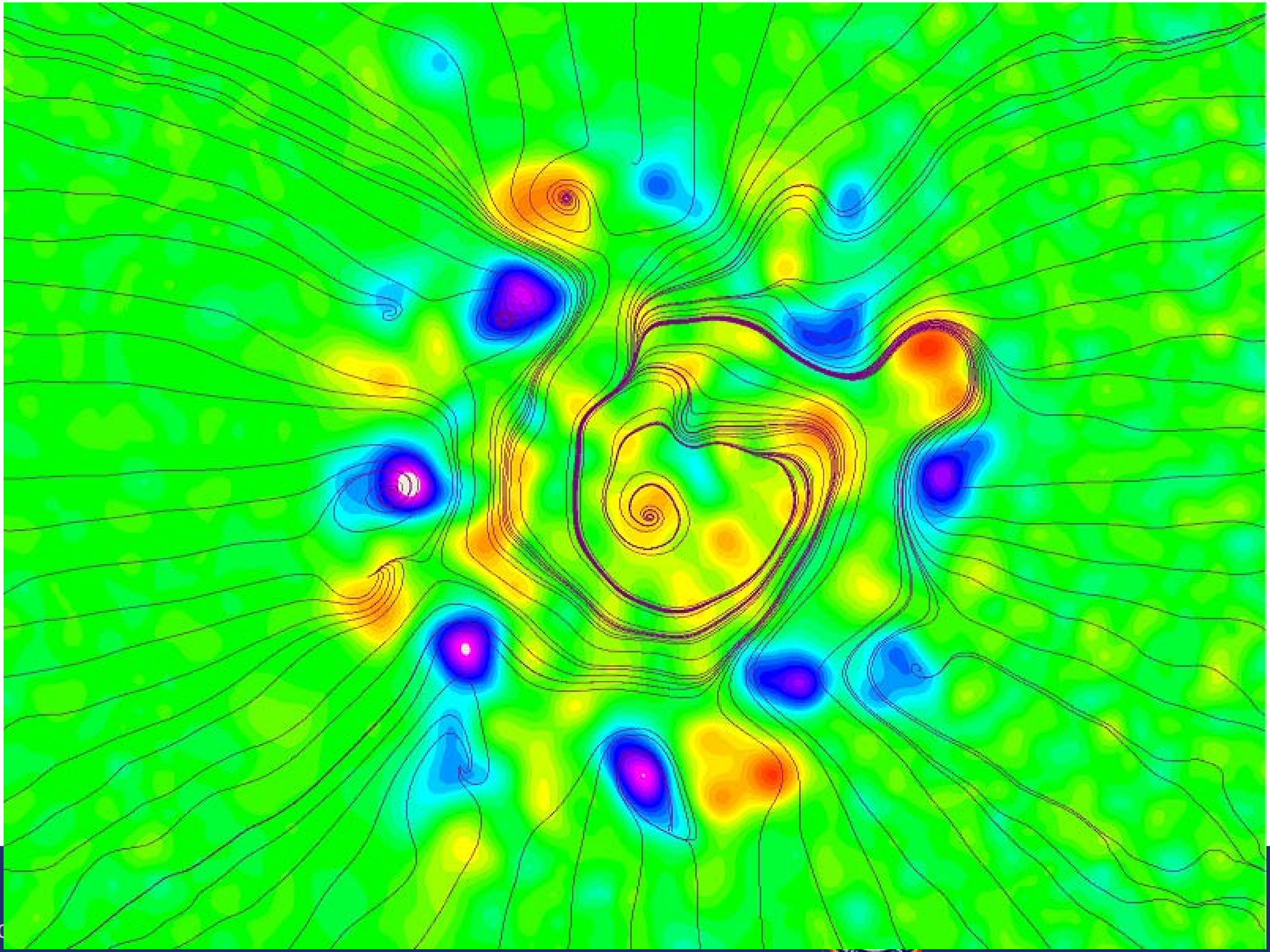
Vector Plot, range 0-1.5 m/s



Vorticity Plot

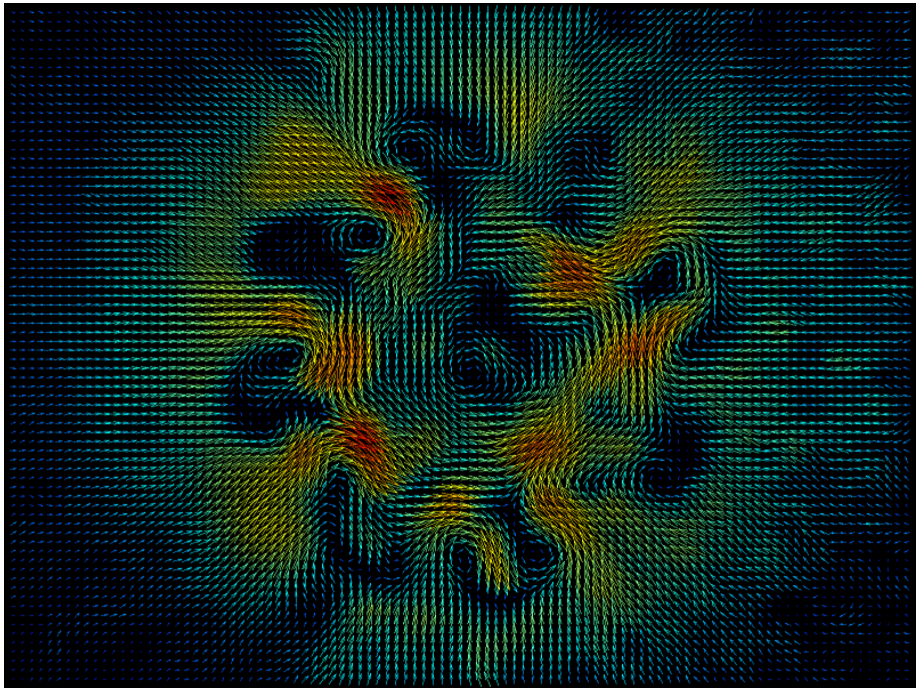


Vorticity and Streamlines



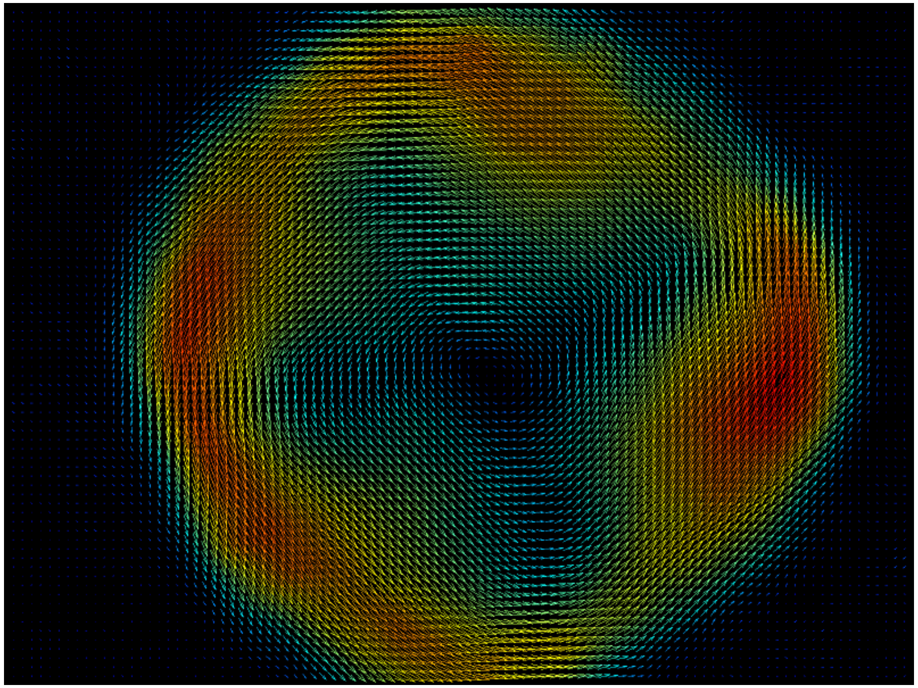
Comparison – Vector Fields

Air Only – Turbulator On



Range 0-1.5 m/s

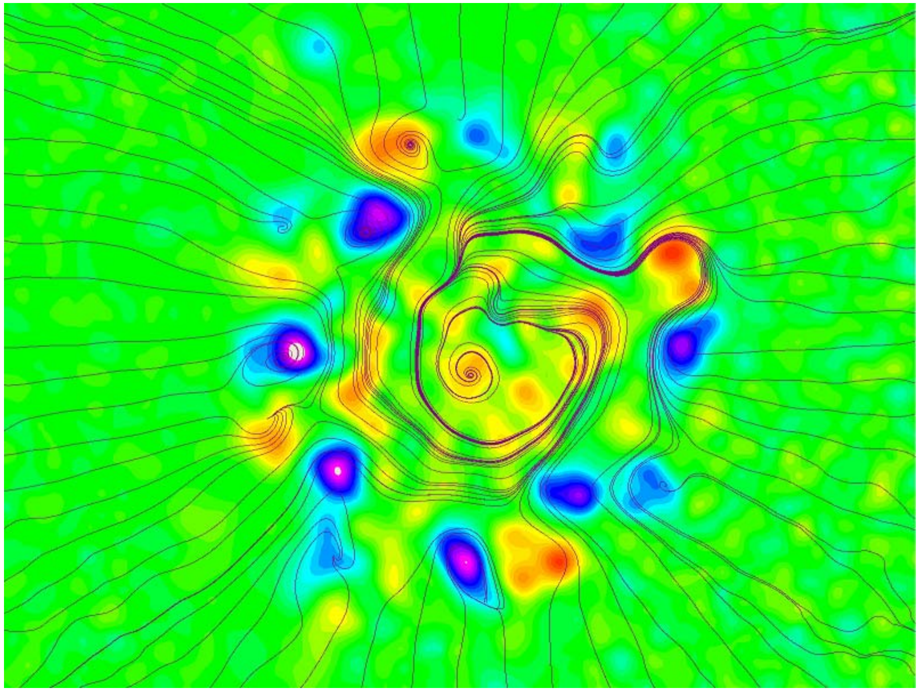
Air Only – Turbulator Off



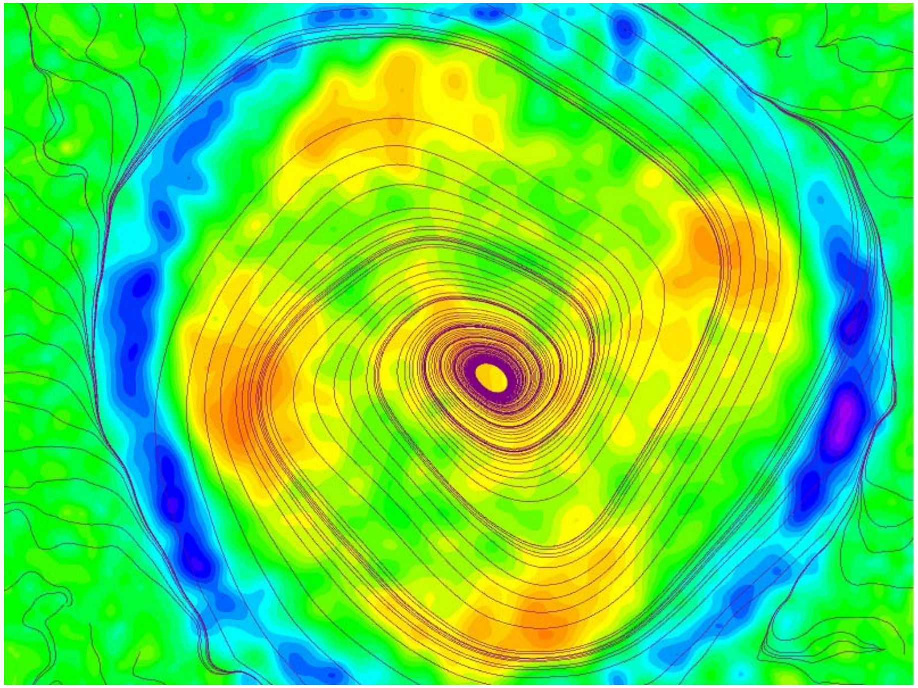
Range 0-4 m/s

Comparison – Vorticity and Streamlines

Air Only – Turbulator On



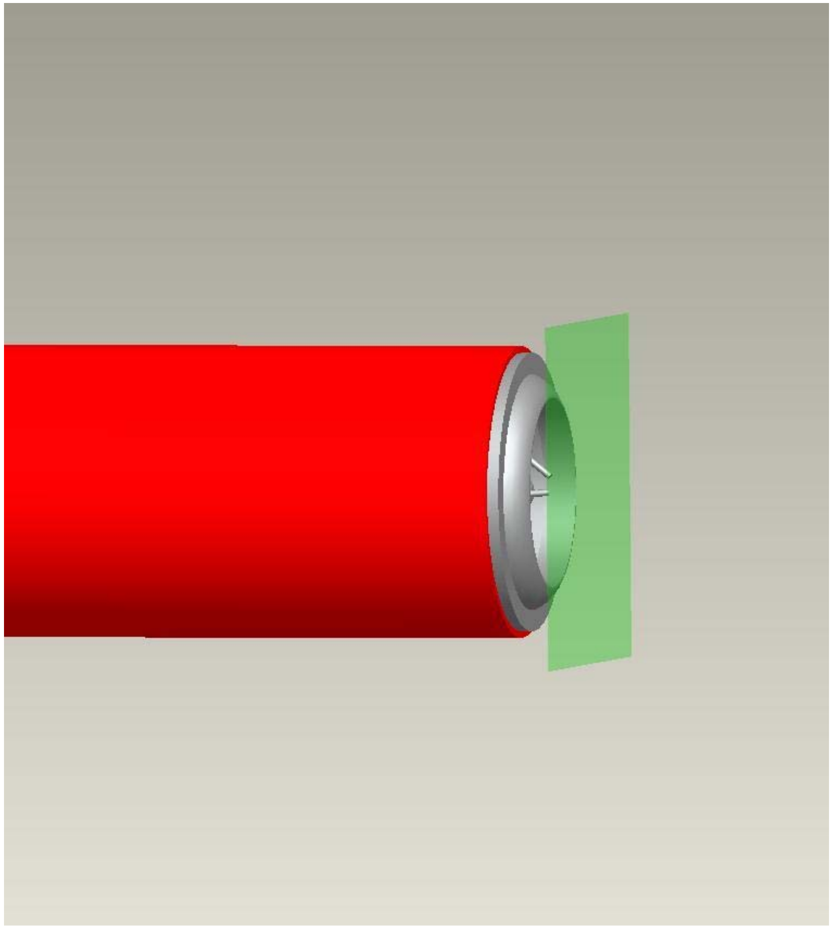
Air Only – Turbulator Off



Analysis

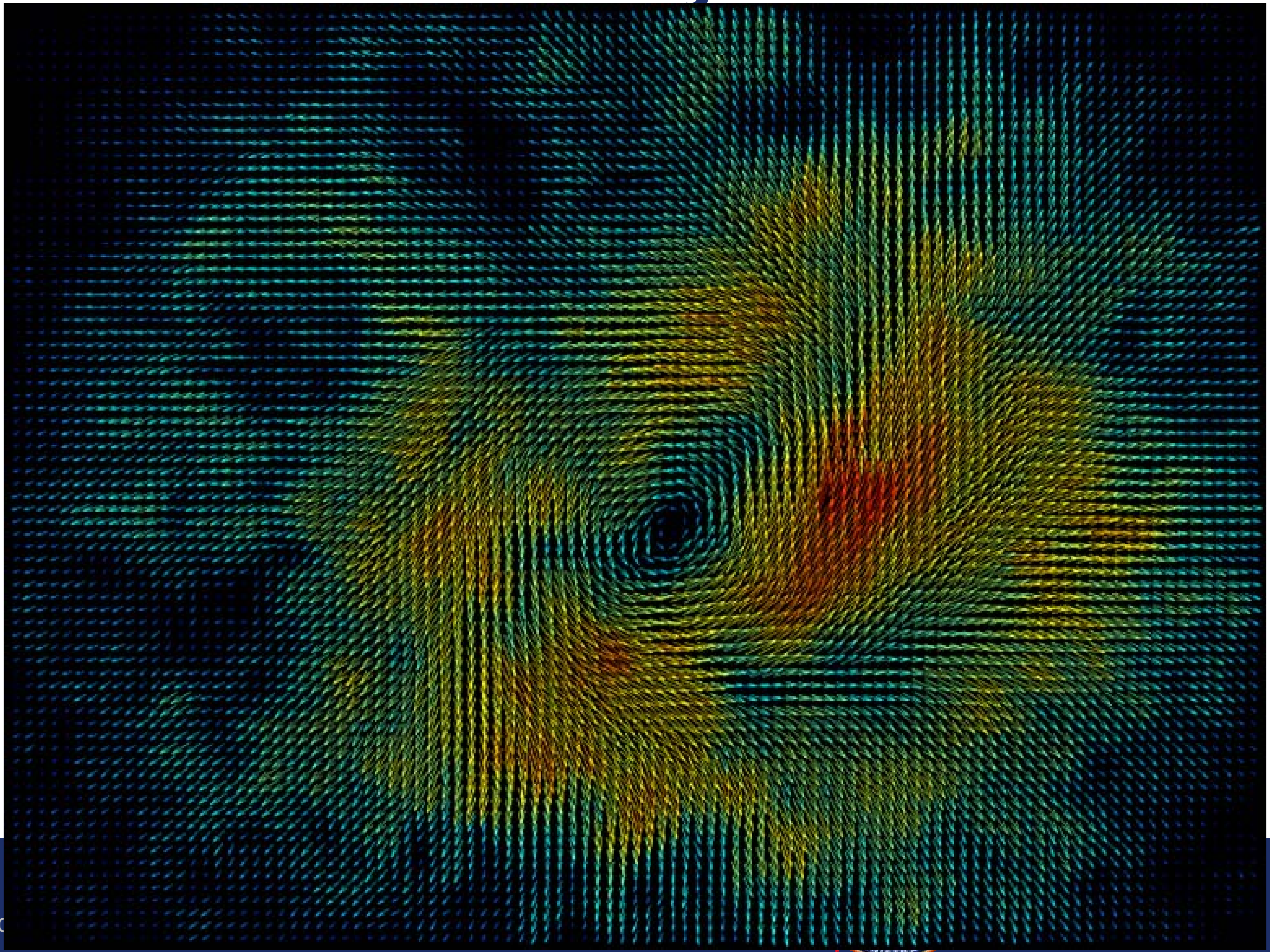
- The effect of the turbulator is apparent in the flow field
- The center of the flow field retains the counterclockwise swirl imparted by the stator
- Each turbulator vane is seen to create a pair of counter-rotating vortices at the edges of the stator-induced swirling flow
- The magnitude of the velocity on the periphery of the flow field is significantly reduced by the action of the turbulator, from ~4 m/s to ~1 m/s
- These counter-rotating vortices are intended to enhance mixing of the air and fuel spray

Exit Flow from Turbulator – Air and Fuel Spray



- In this case, fuel spray is used as flow seeding to visualize the effect of the burner airflow on the fuel spray
- Investigating the effect of the previously studied air flow pattern on the fuel spray

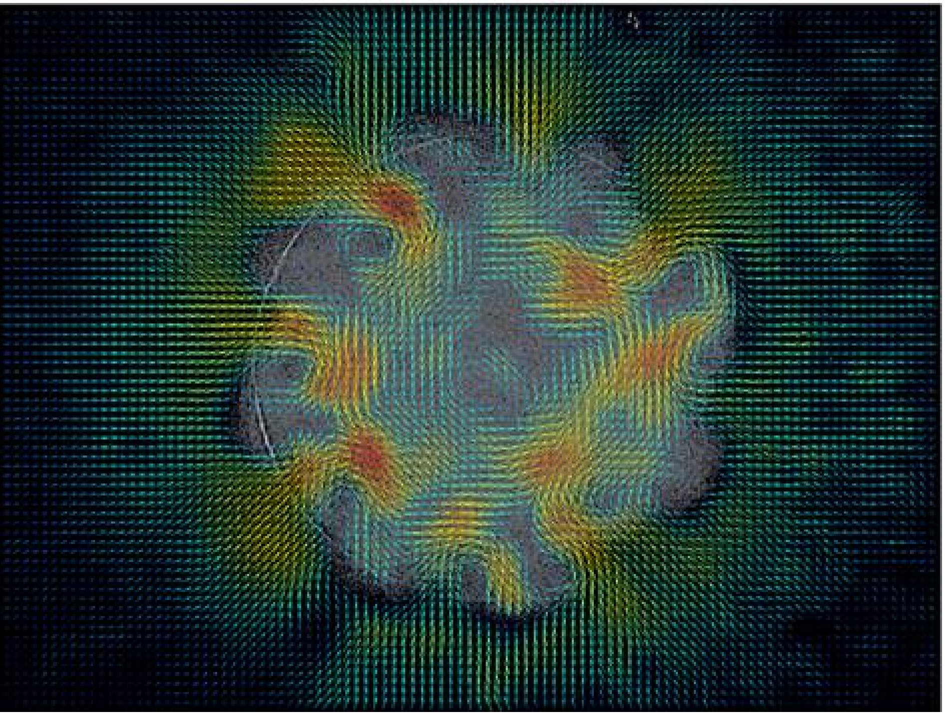
Air and Fuel Spray Exiting from Turbulator – Velocity Field

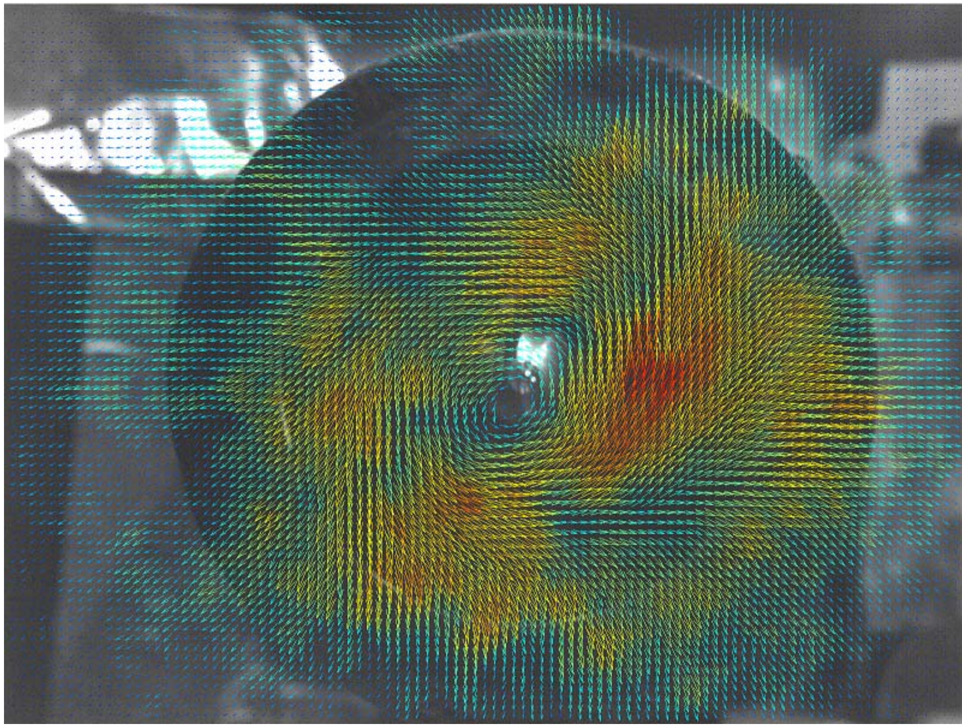


Comparison

Air Only – Turbulator On

Air & Fuel Spray – Turbulator On

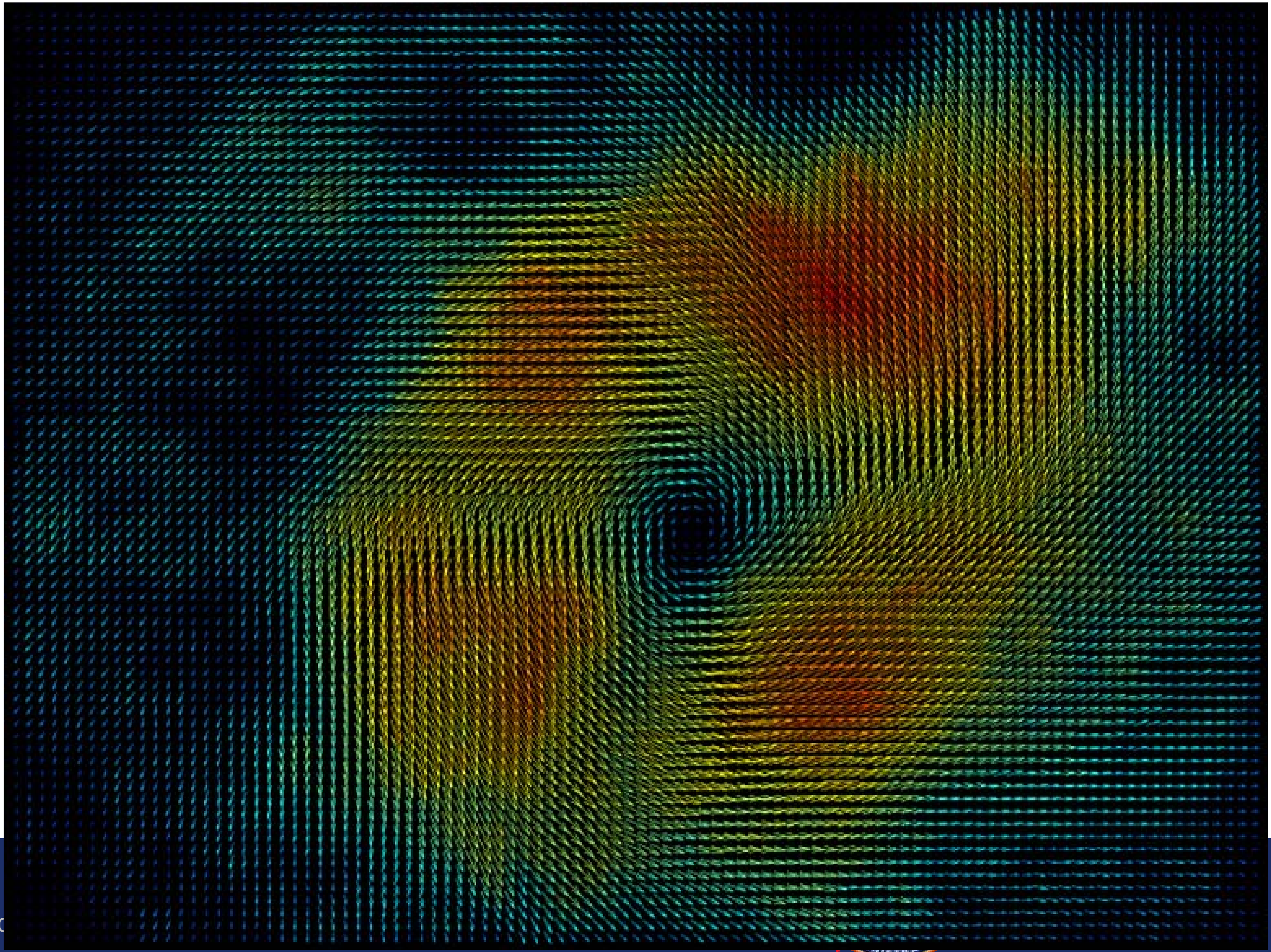




Range 0 – 1.5 m/s

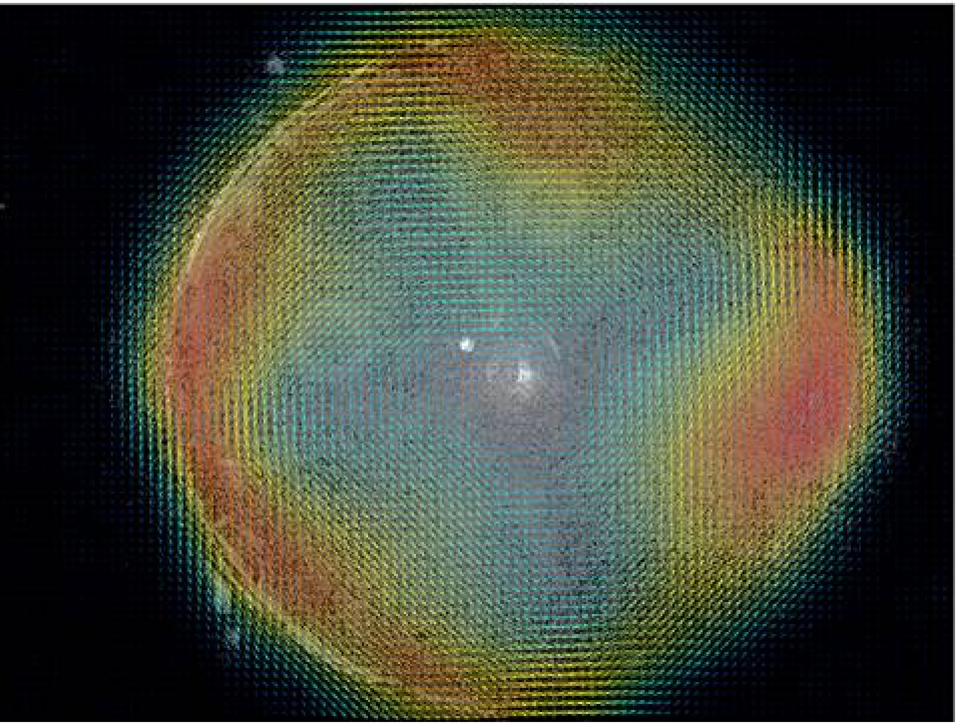
Range 0 – 1.3 m/s

Air and Fuel Spray Exiting Draft Tube, No Turbulator



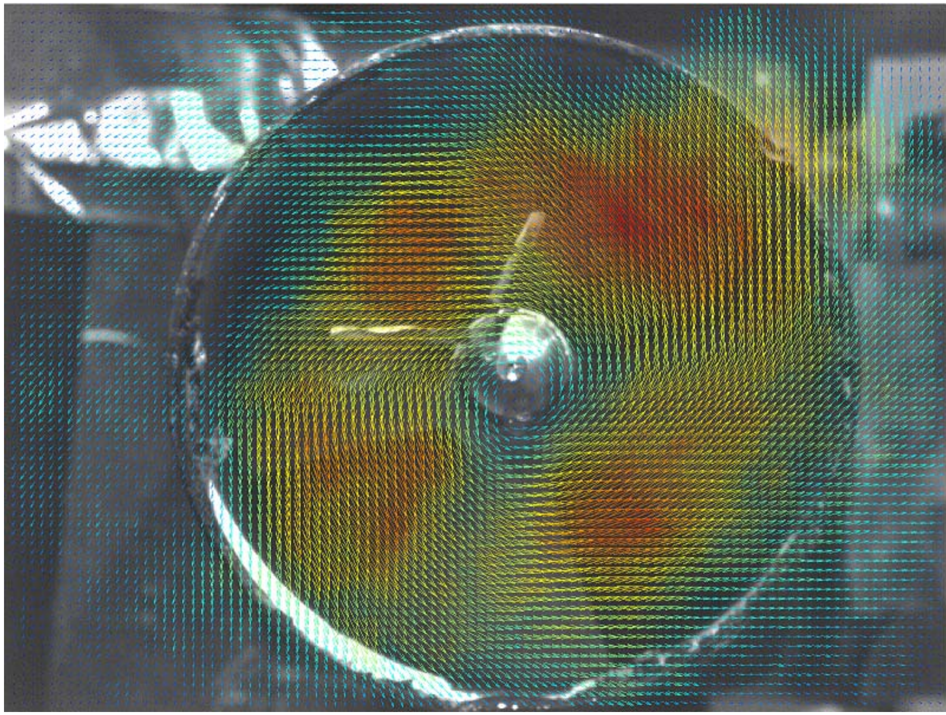
Comparison

Air Only – Turbulator Off



Range 0-4 m/s

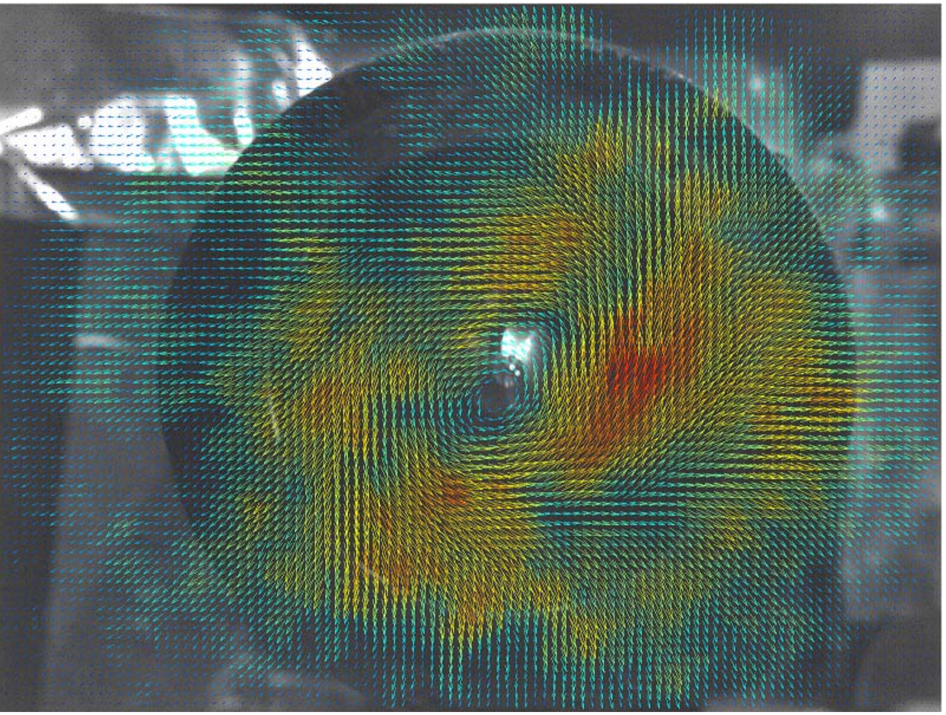
Air & Fuel Spray – Turbulator Off



Range 0-1.6 m/s

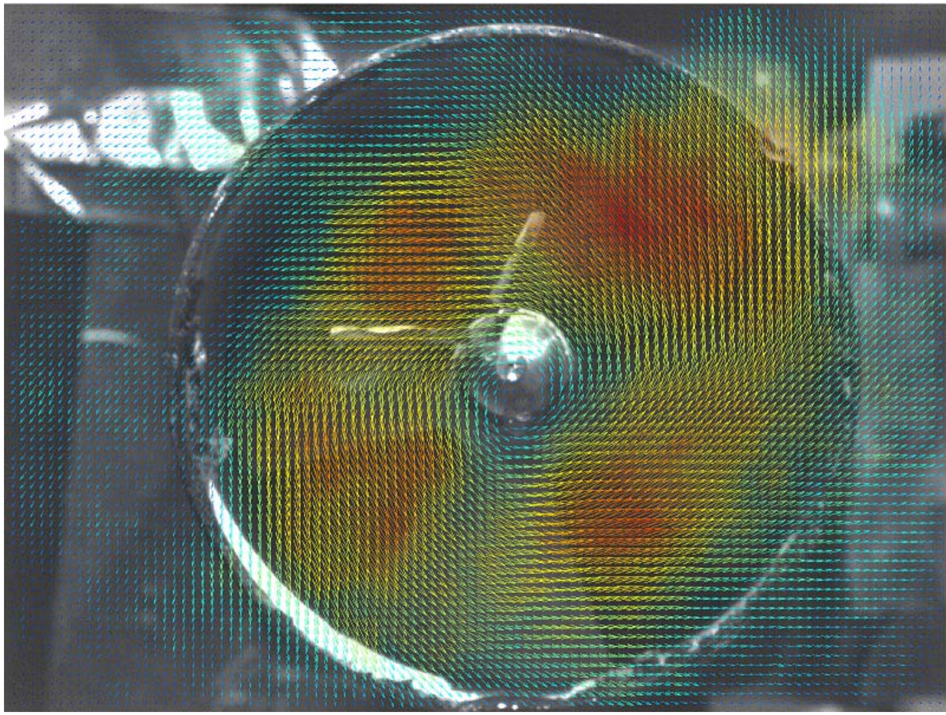
Comparison

Air & Fuel Spray – Turbulator On



Range 0-1.3 m/s

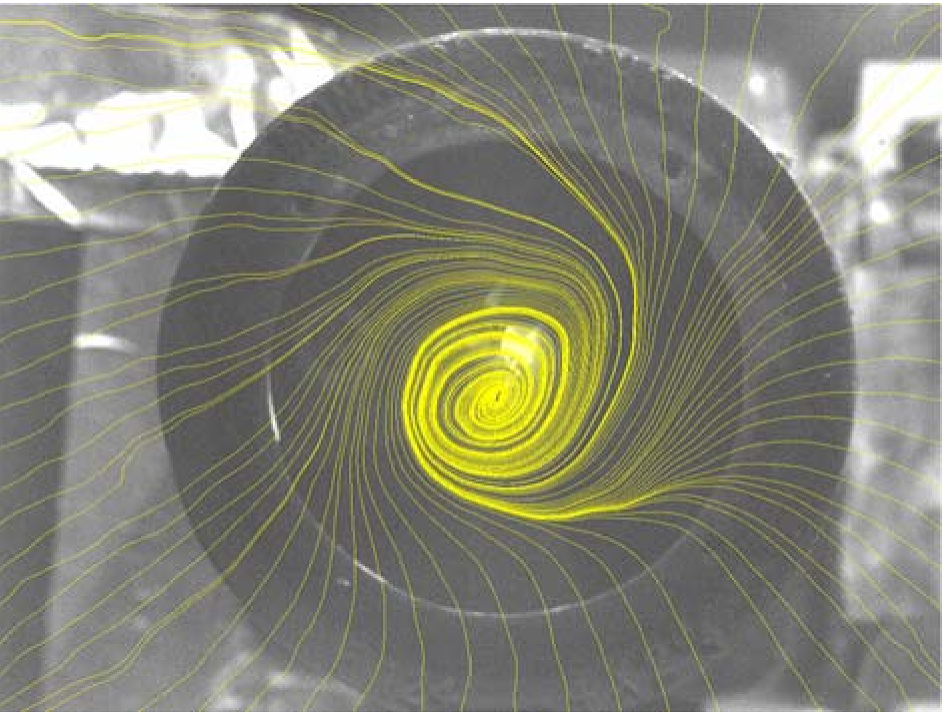
Air & Fuel Spray – Turbulator Off



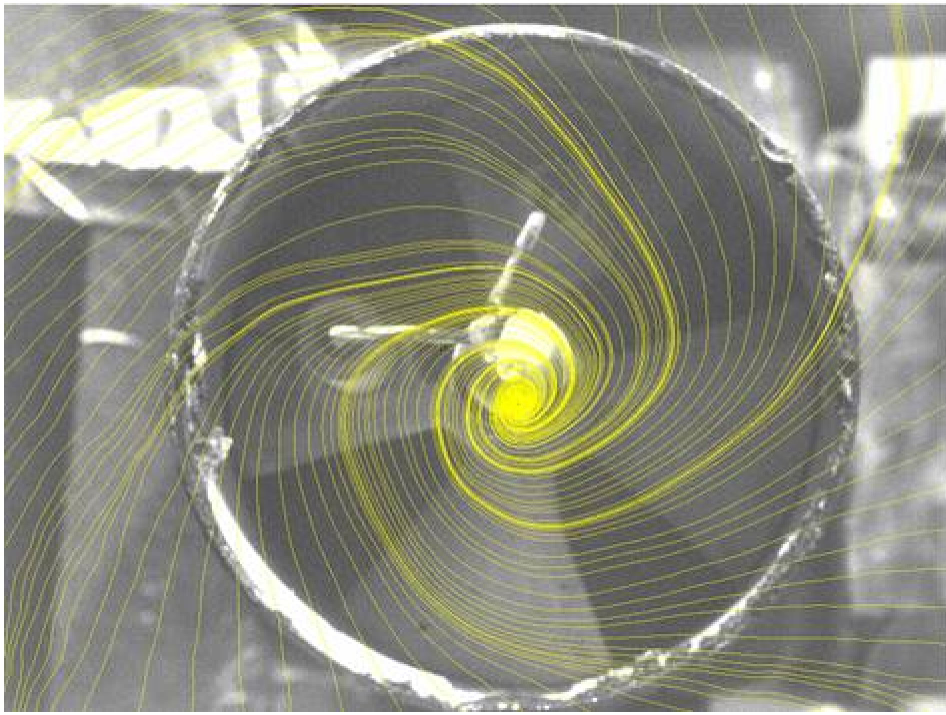
Range 0-1.6 m/s

Comparison - Streamlines

Air & Fuel Spray – Turbulator On

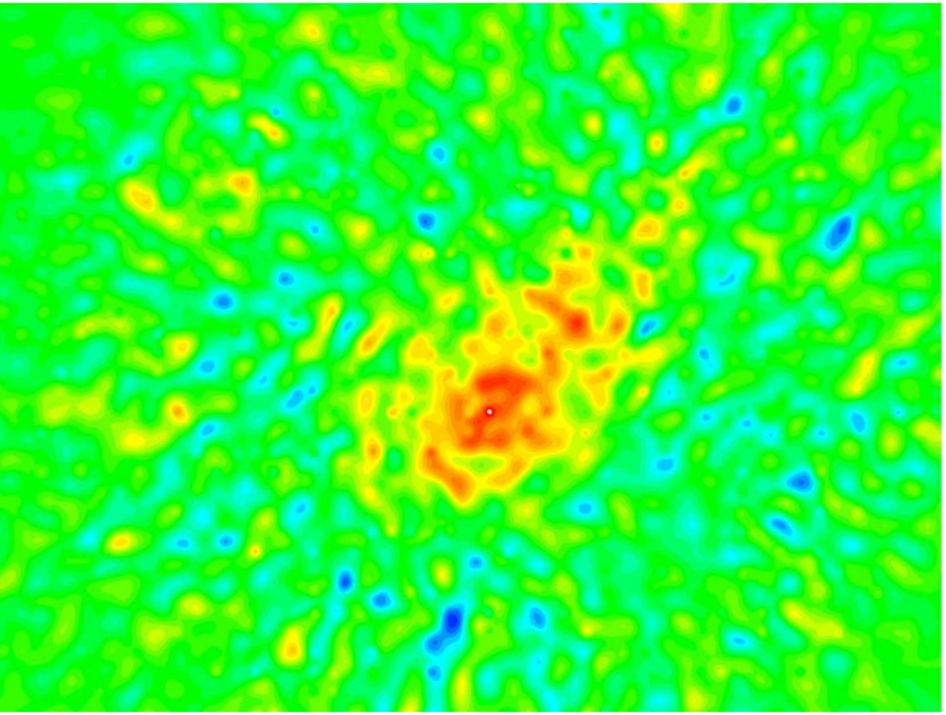


Air & Fuel Spray – Turbulator Off

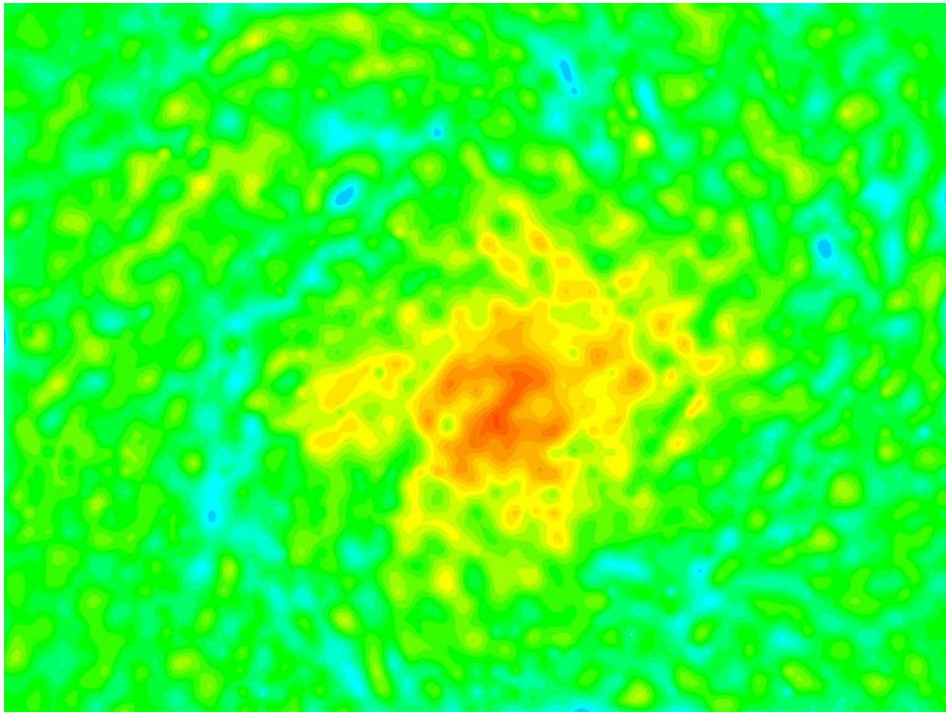


Comparison – Vorticity Fields

Air & Fuel Spray – Turbulator On

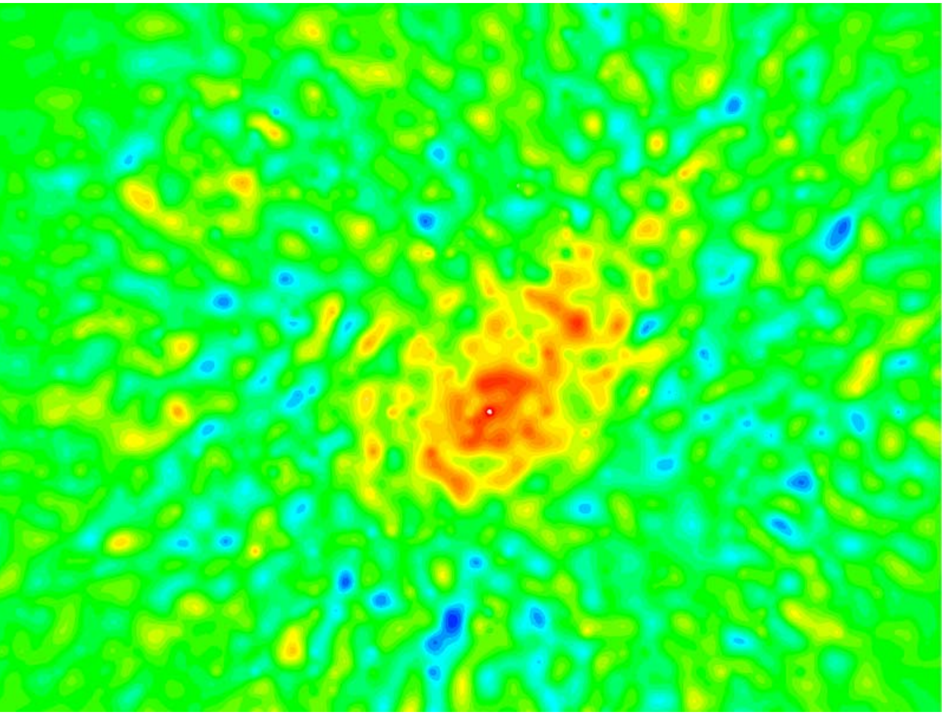


Air & Fuel Spray – Turbulator Off

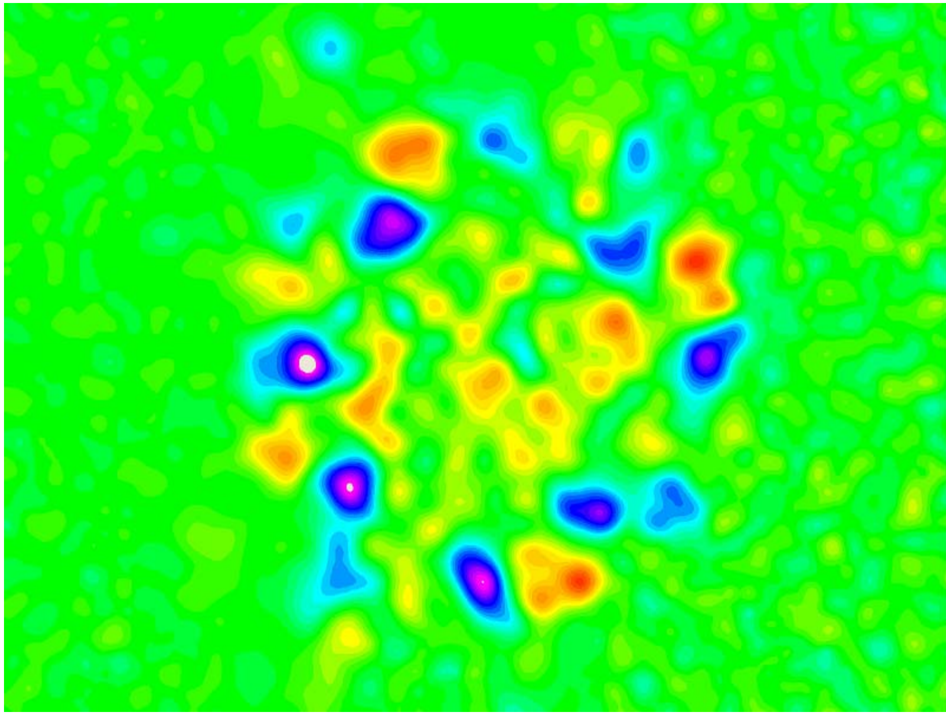


Comparison – Vorticity Fields

Air & Fuel Spray – Turbulator On

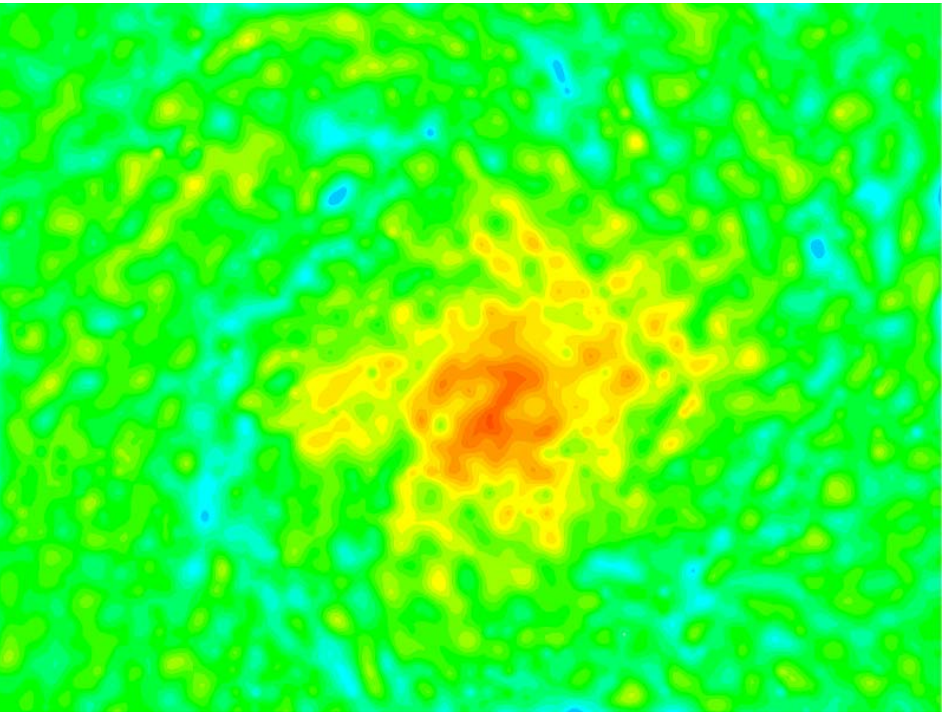


Air Only – Turbulator On

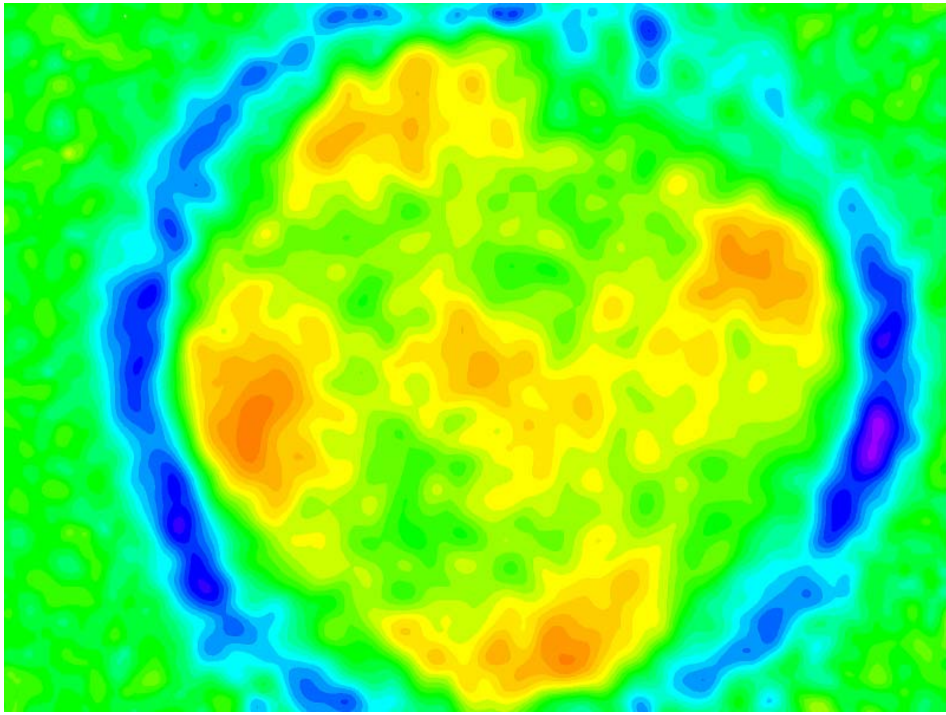


Comparison – Vorticity Fields

Air & Fuel Spray – Turbulator Off



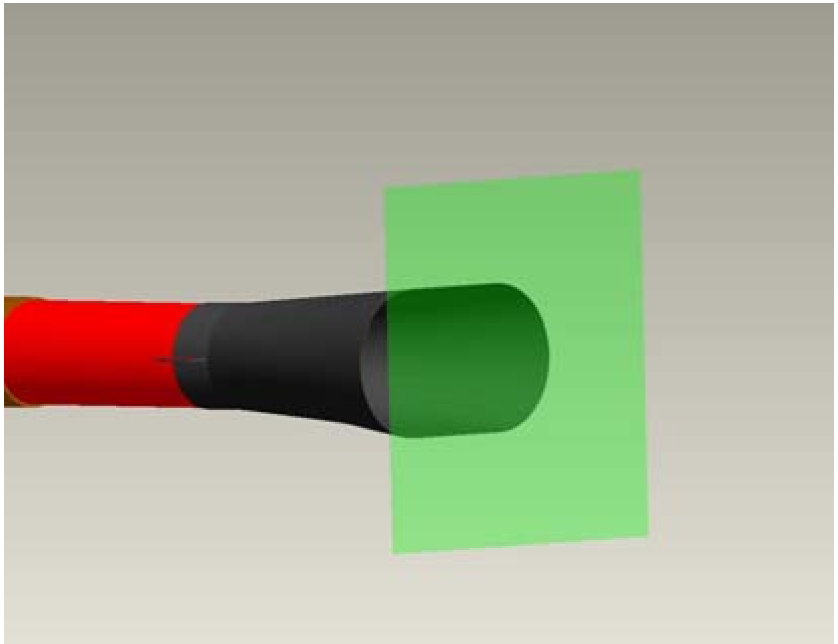
Air Only – Turbulator Off



Analysis

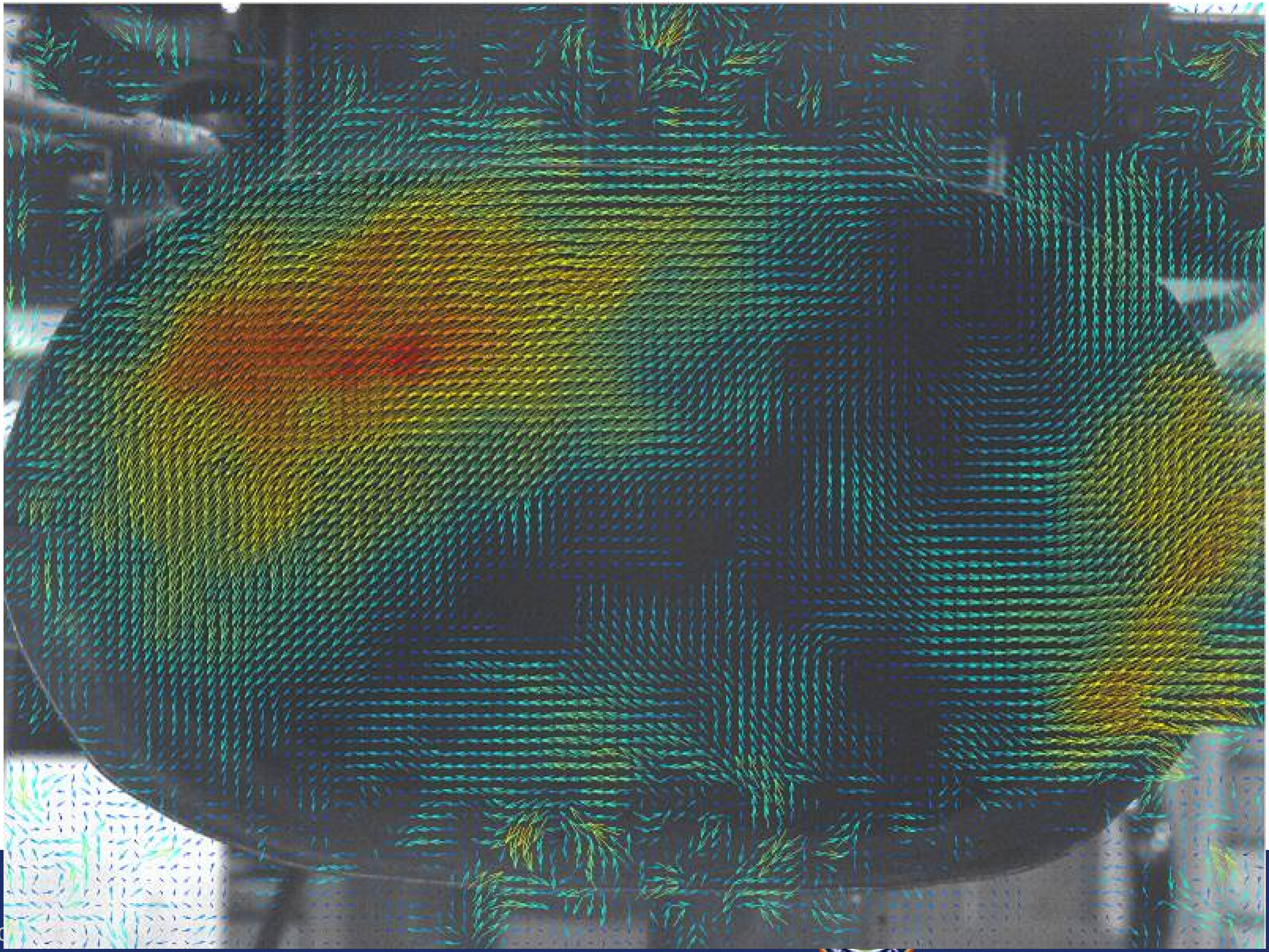
- Spray droplets are not as easily entrained in the air flow, due to higher mass and momentum than the Aluminum Dioxide particles
- The effect of the turbulator is seen to restrict the center swirling flow from growing, and shearing the outer layers of the swirl to mix the air and spray droplets
- Spray droplets have lower velocity in the non-turbulator case when compared to Aluminum Dioxide particles (1.6 m/s compared to 4 m/s)
- Comparison of the vorticity maps shows that for the turbulator on case, smaller counter-rotating vortices are still evident on the periphery of the swirling flow, whereas for the turbulator off case, strong positive vorticity is located in the center while negative vorticity is on the edges of the flow

Exit Flow From Burner Cone

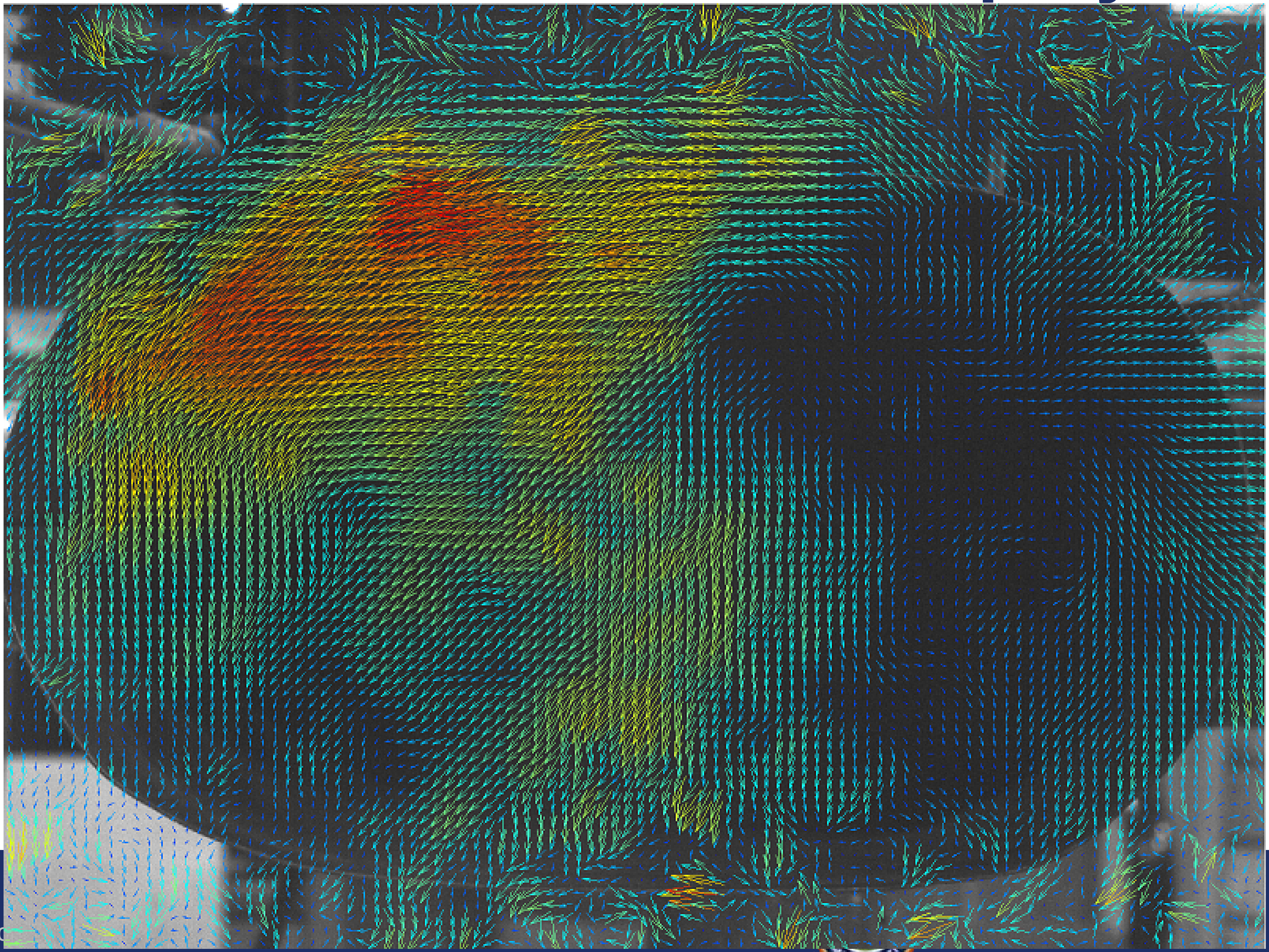


- Measurement plane was 3” from and parallel to burner cone exit plane
- Airflow was seeded with Aluminum Dioxide ceramic particles
- Spray droplets were also used to visualize the effect of the airflow on the fuel spray exiting the cone

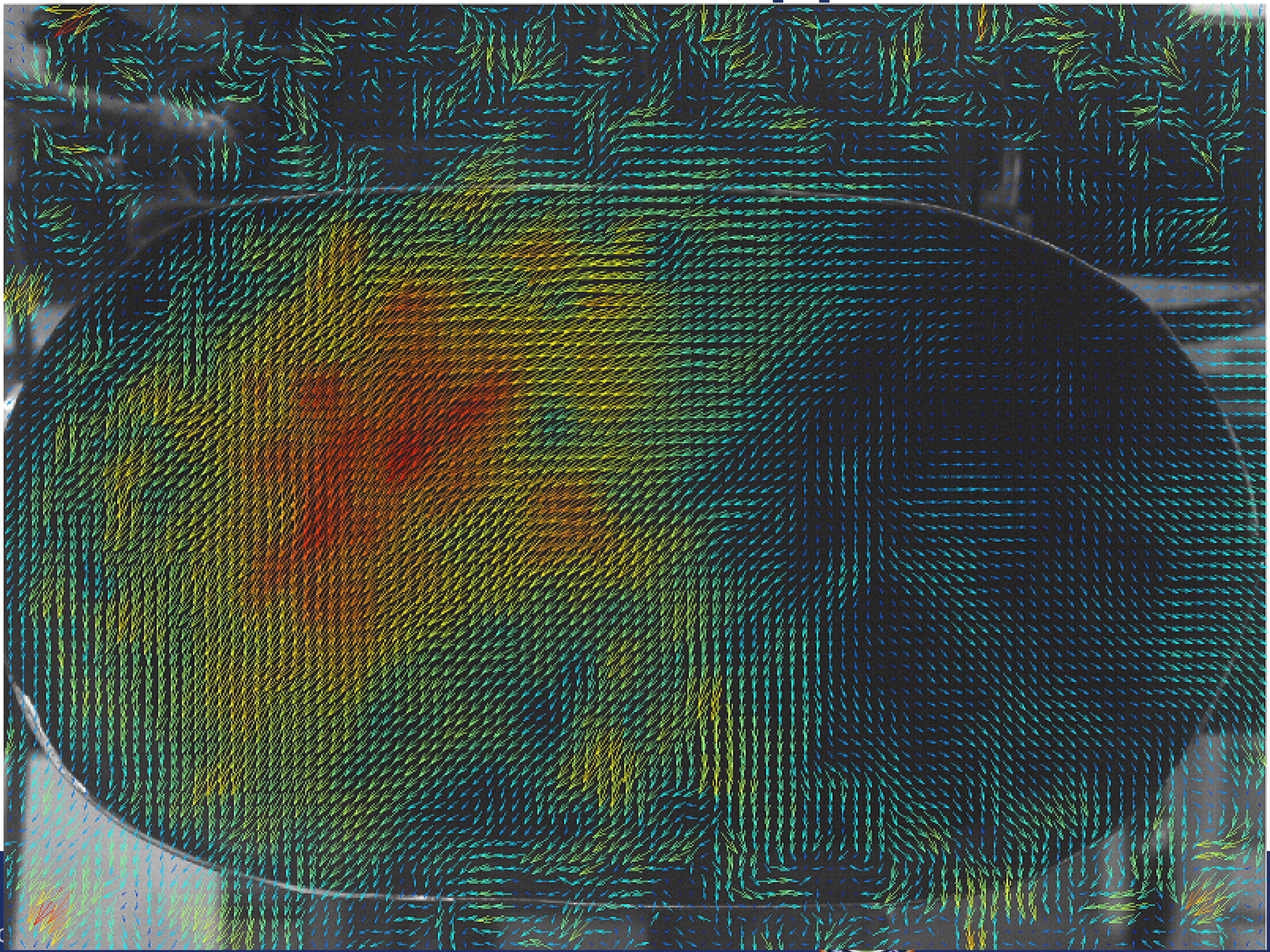
Vector Field – Airflow



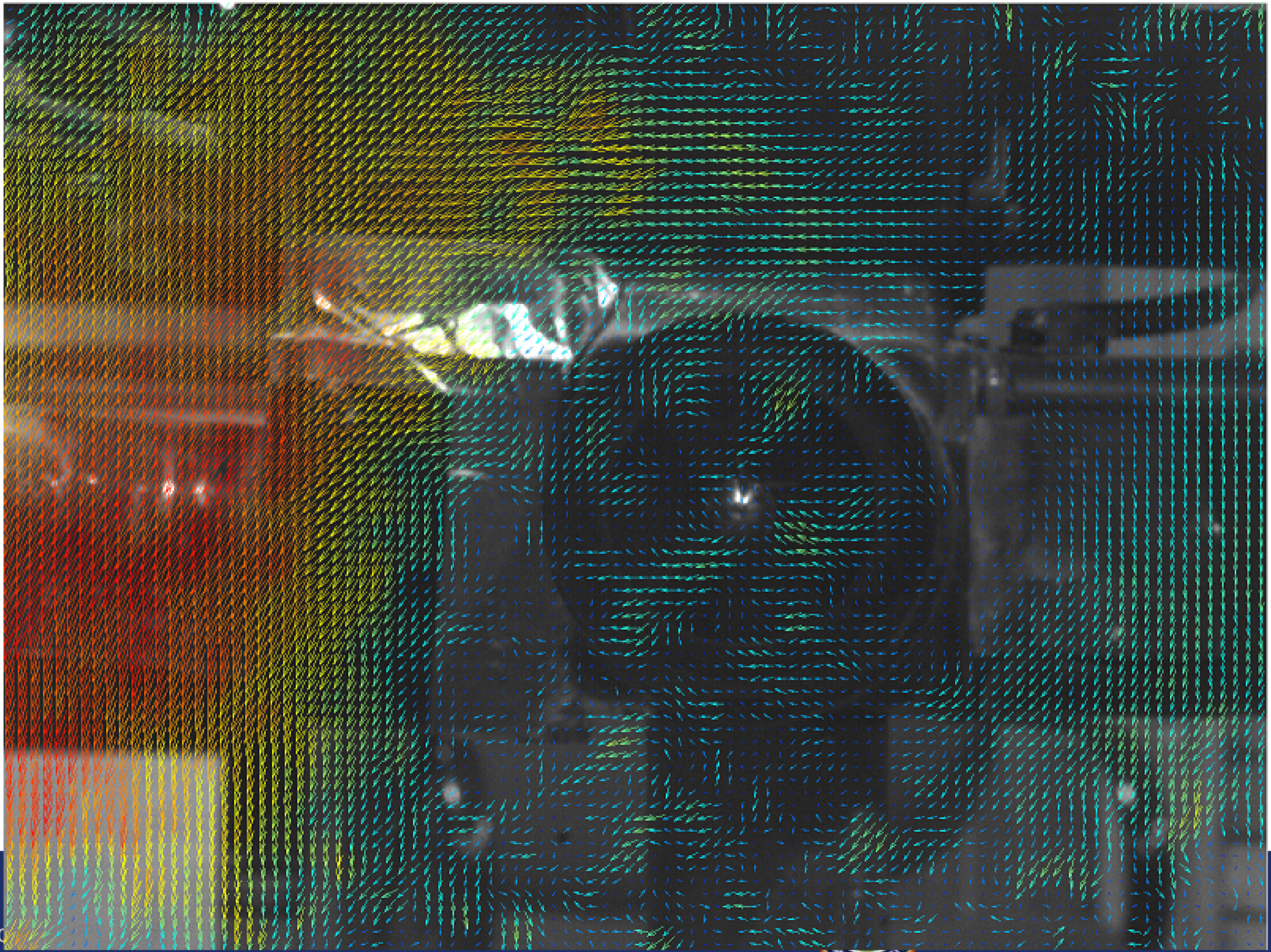
Vector Field – Air and Fuel Spray



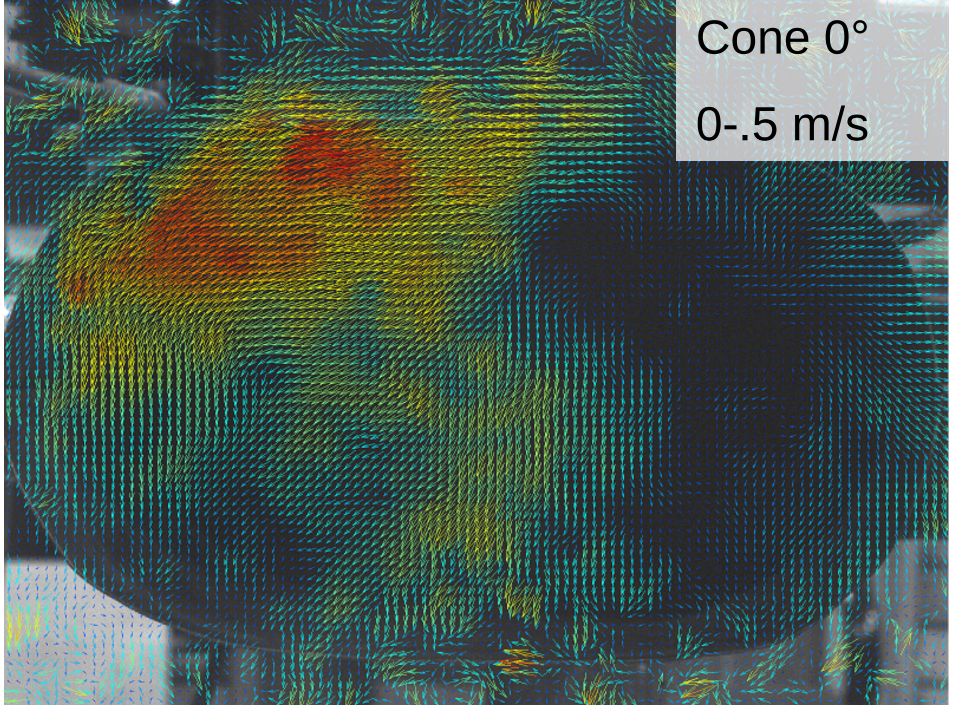
Vector Field – Cone Flipped 180°

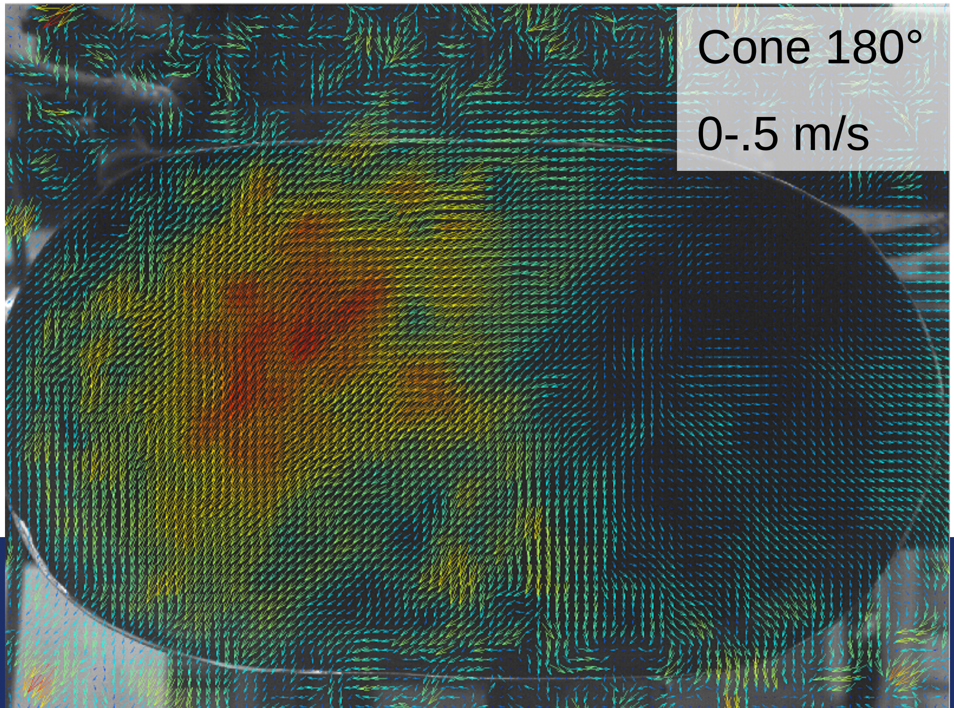


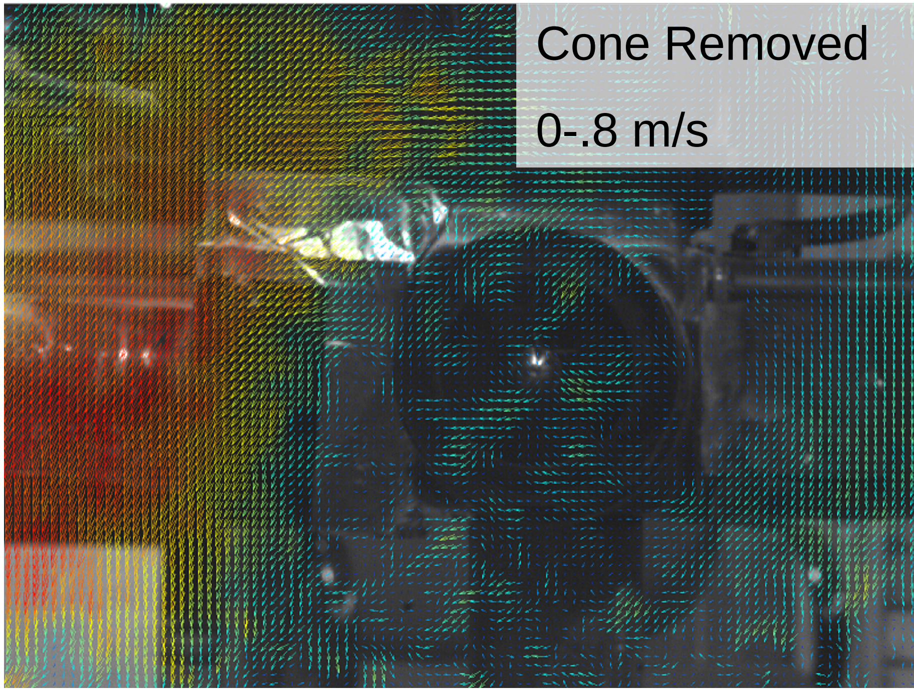
Vector Field – Cone Removed



Comparison



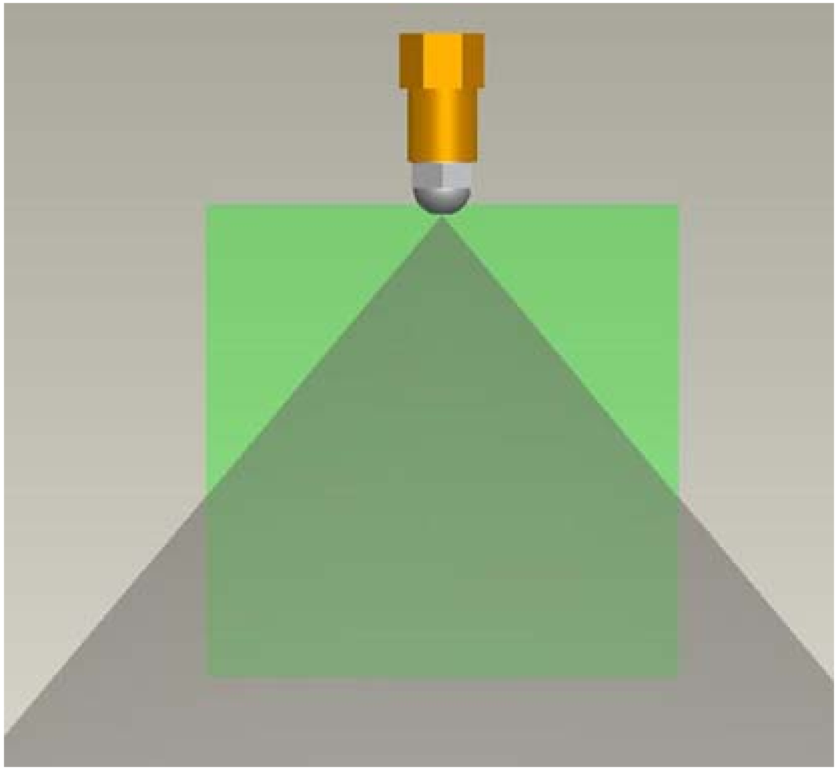




Analysis

- The flow field exiting the cone was similar for the case of air only and air and fuel spray
- The counterclockwise swirling motion is still evident after the flow traveled through the length of the cone, although the swirl seems to “break up” near the top and bottom horizontal surfaces of the cone
- The growth of the swirling flow through the cone may cause the edges of the flow to hit the inner surfaces of the cone, disrupting the flow
- Rotating the cone 180° has a slight effect on the flow, however the magnitude of the higher velocity region in the upper left corner is unchanged
- Removing the cone and measuring in the same plane showed a region of high velocity on the left side, which may be due to the swirl flow a non-quiescent laboratory atmosphere

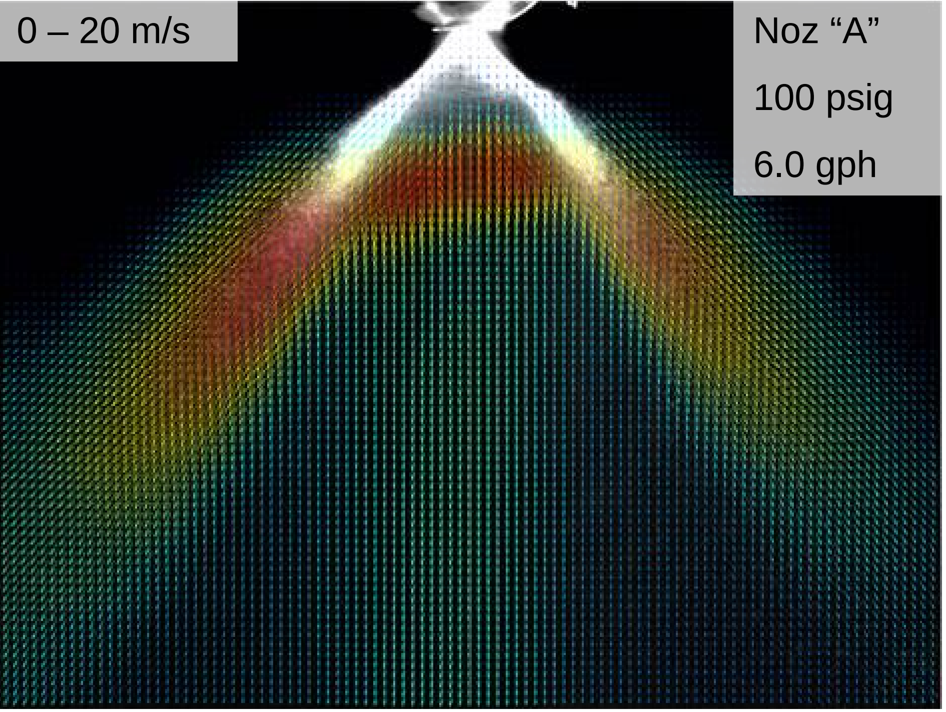
Spray Nozzle Visualization

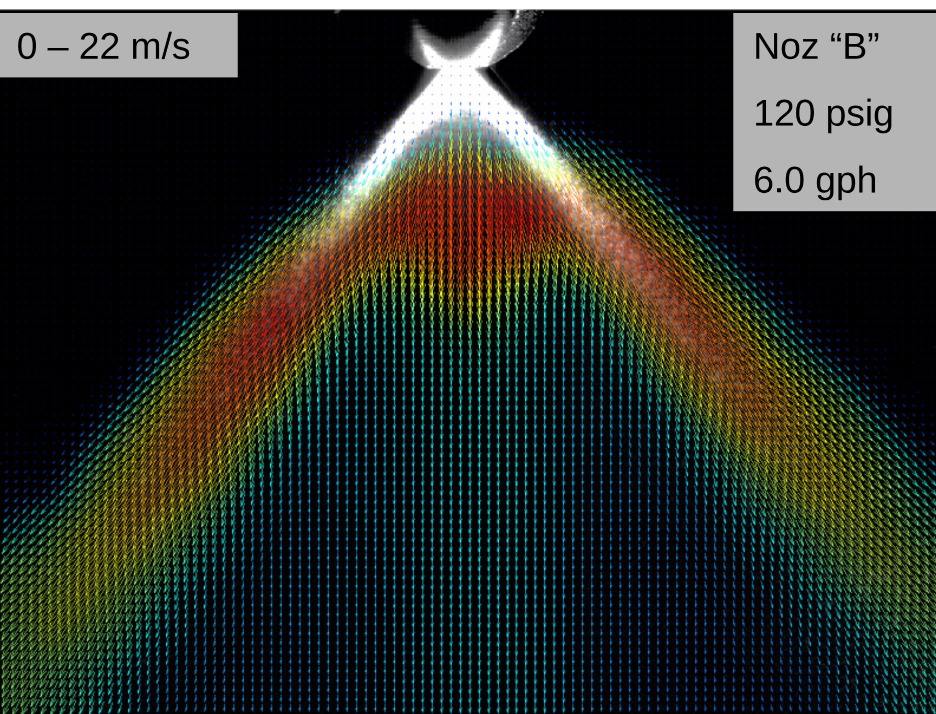


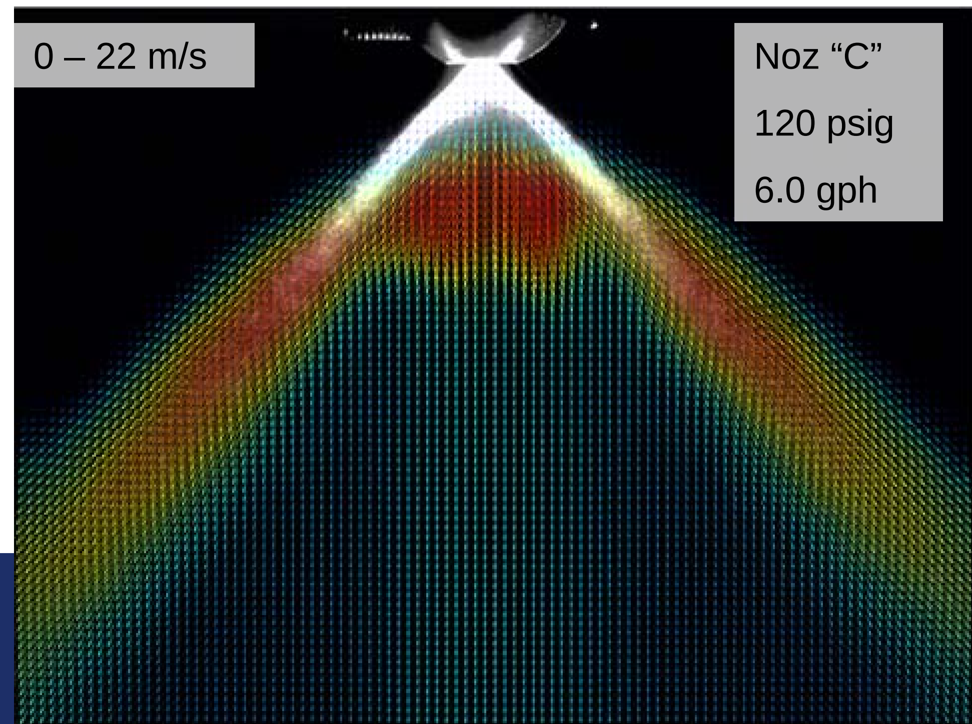
- **Water is substituted for fuel**
- **3 different nozzles were compared**
  - "A": 6.0 GPH 80° Hollow Cone
  - "B": 5.5 GPH 80° Hollow Cone (Old Style)
  - "C": 5.5 GPH 80° Hollow Cone (New Style)
- **Nozzle "B" was measured at 3 different inlet pressures**
  - 80 psig
  - 100 psig
  - 120 psig
- **Nozzle "B" was also measured at 6 different axial planes**

Comparison

3 different nozzles at 6.0 GPH flow rate

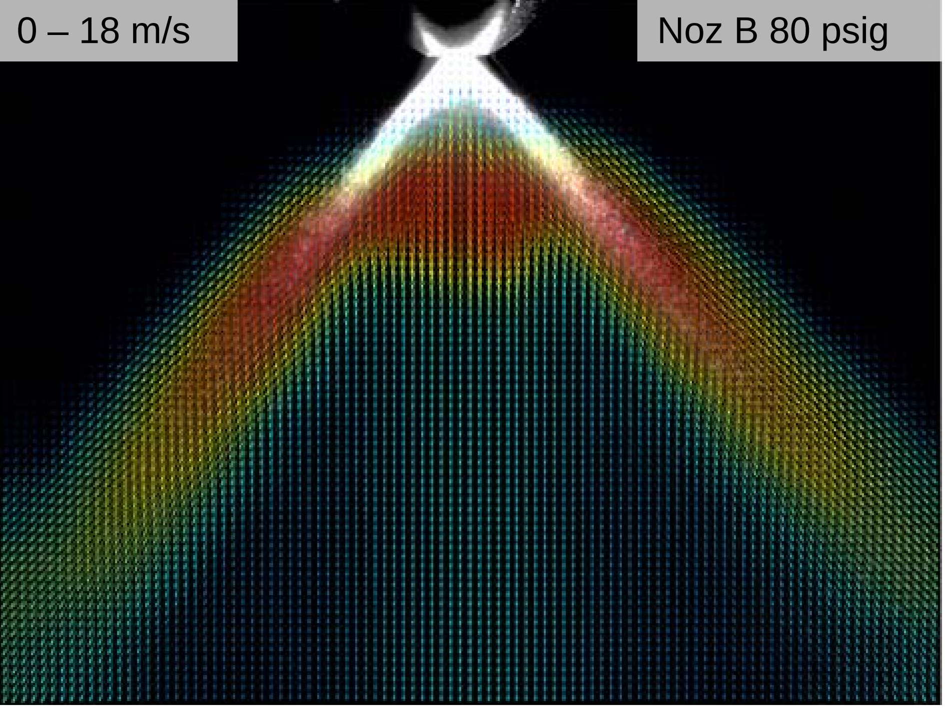


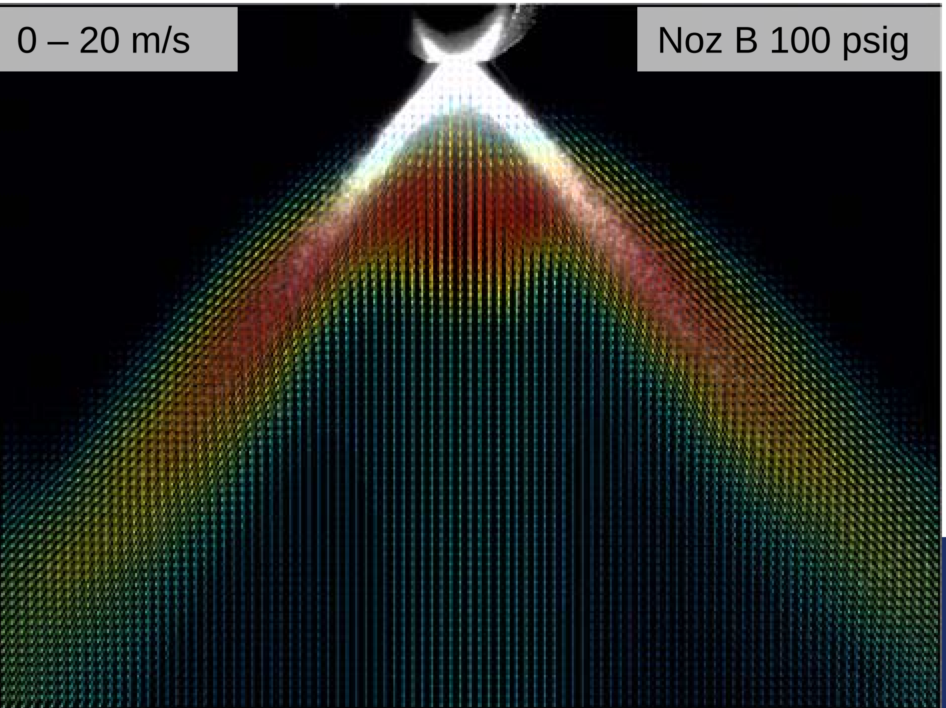


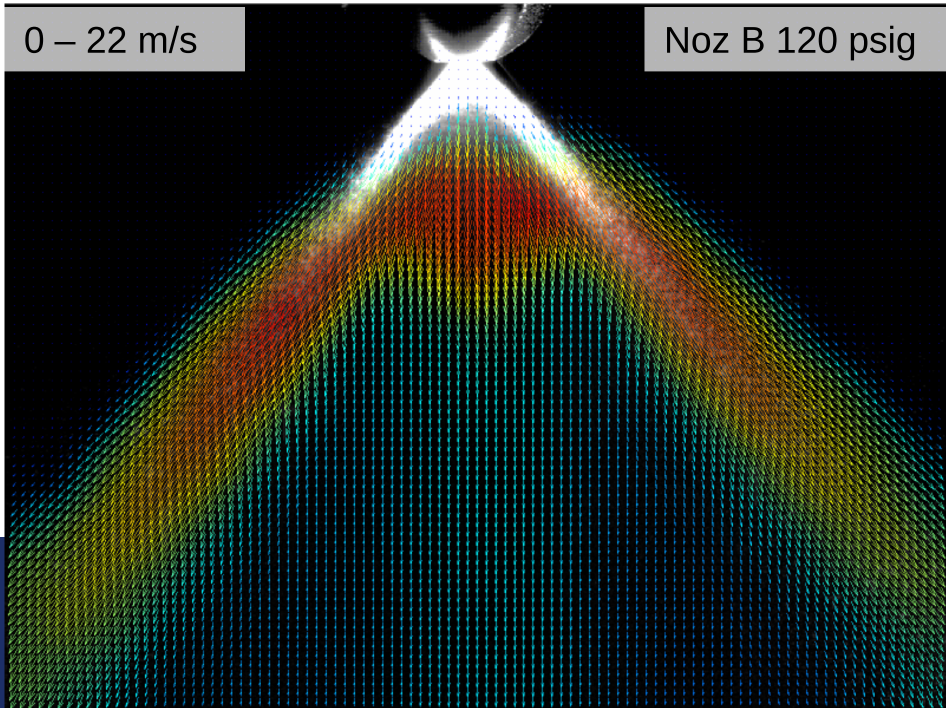


Comparison

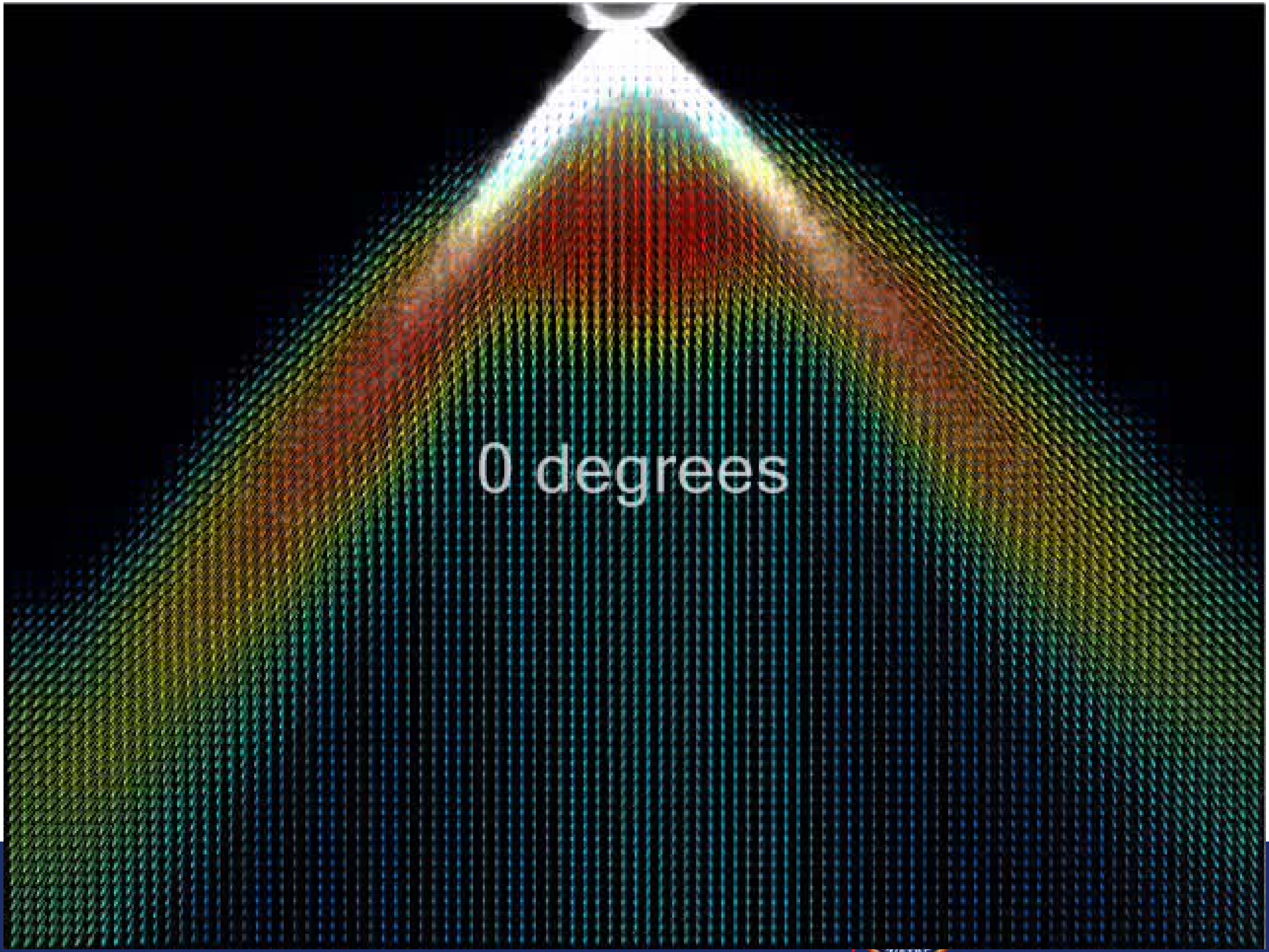
Nozzle B measured at 3 different inlet pressures







Nozzle “B” Rotational Measurements



Analysis

- **Comparison of nozzles A, B, and C at 6.0 GPH:**
  - Nozzle A had an overall lower velocity than B and C, which had a very similar velocity map
  - Nozzle A seemed more asymmetric than B and C
  - Although the same flow rate was achieved by varying the inlet pressure, the spray velocity will not be the same for different nozzles due to different orifice sizes
- **Comparison of different inlet pressures for nozzle B:**
  - As the inlet pressure increased, the magnitude of the velocity field increased
  - Increasing the inlet pressure also led to a greater penetration depth of the high velocity regions in the cone
- **Comparison of different measurement planes for nozzle B:**
  - Different measurement planes were observed to have slightly different velocity maps, although the magnitude of the velocity was relatively unchanged

Preliminary Flame Measurements

- Initial measurements were made on the burner flame approx 3 inches from burner cone exit plane
- Narrow band filters were necessary to block all wavelengths except for 532 nm laser light
- Flame is extremely luminous, soot emission at 532 is much stronger than seed particle emission
- An external electro-optic shutter is necessary to avoid over-lightening of the second frame

Summary

- PIV can be used to analyze the various components of the FAA Fire Test Burner
- Successful measurements were made of the burner exit air flow, spray nozzle flow, and combined air and fuel flow
- An external shutter is necessary to make measurements in the burner flame