Study of Swirling Jet on an Impingement Surface

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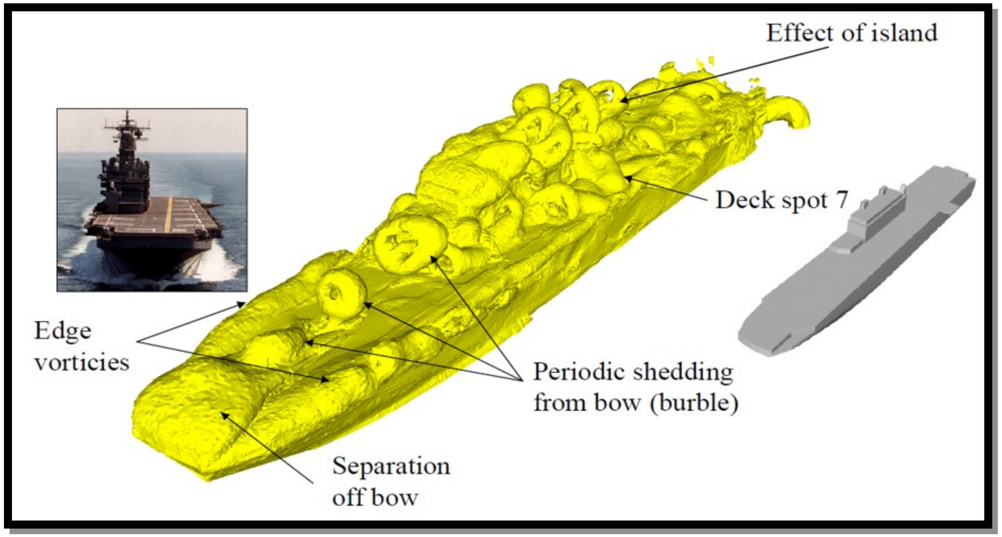
Background

- Vortex flow is seen in many applications:
  - “Burble” effect on aircraft carriers [1]
  - Vortex wake at airports
- Impingement wall could be a potential solution to reducing vortex wake and “burble” effect
- How does vortex flow interact with angles impingement surfaces?



Airflow Simulation of Aircraft Carrier [13]

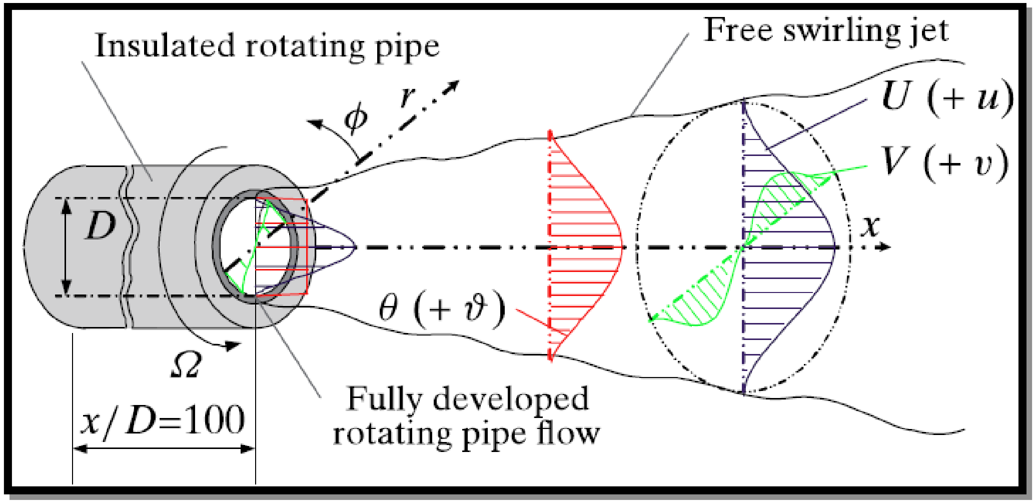
Physics of Jets and Vortex Flow

$$Incompressible\ Naiver - Stokes\ equation{:}\ \frac{1}{r}\frac{\partial}{\partial r}(rW) + \frac{\partial U}{\partial x} = 0$$

$$Swirl\ Intensity{:}\ \ S_{\emptyset x} = \left[\int_0^{\infty} r^2\, UV dr\right]\left[R\int_0^{\infty} r\left(U^2 - \frac{1}{2}V^2\right)\, dr\right]^{-1}$$

$$Reynolds\ Number{:}\ Re = \frac{U * D}{v}$$

$$Swirl\ Number{:}\ S = \frac{V}{U}$$

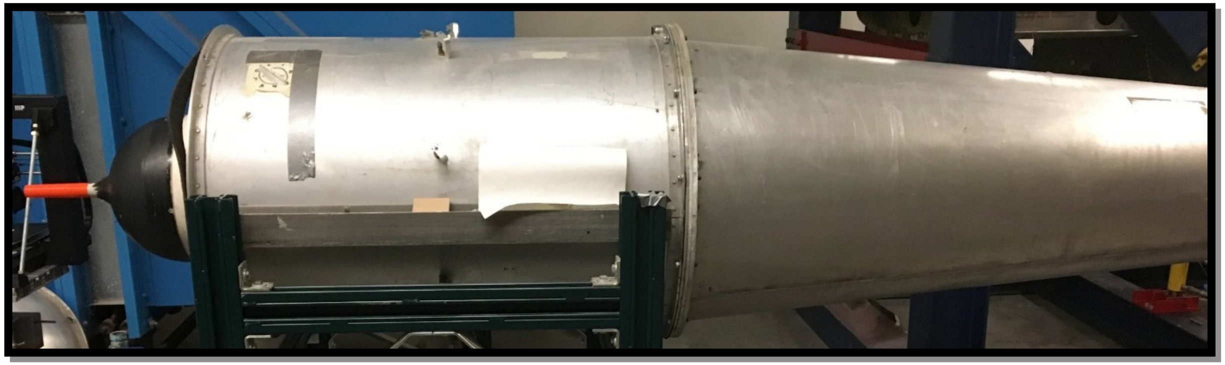


Free Flow Developing Swirling Jet [12]

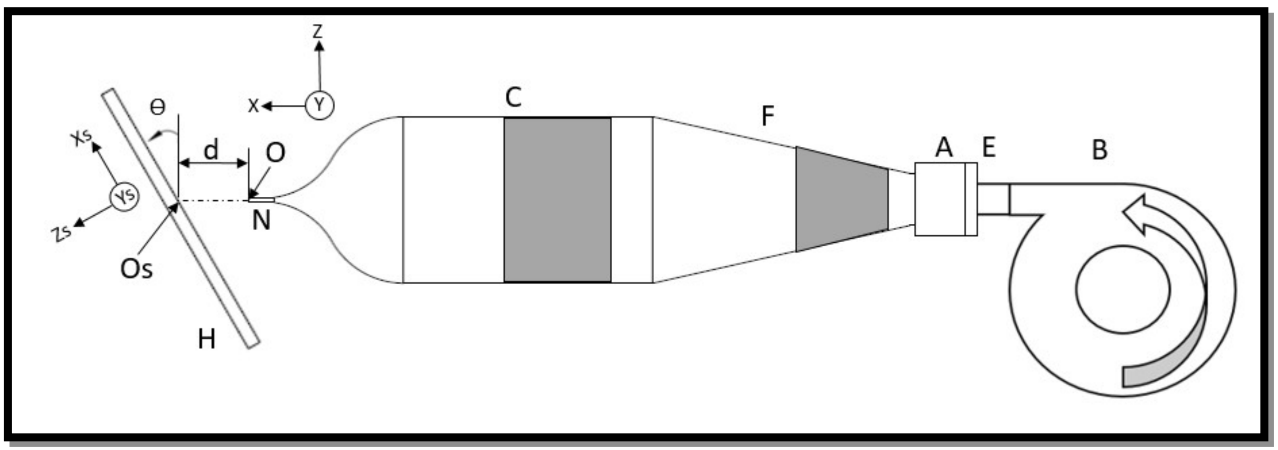
Research Objectives

- Compare diverging/converging blower system to previous studies to validate setup and instrumentation methods.
  - Measure axial jet stream profile of tripped nozzle setup
- Develop flow visualization technique to capture flow field interactions
- Develop three swirling jet stream nozzles with varying swirl number
  - Characterize axial and azimuthal profiles of the unimpeded flow for each nozzle
- Characterize flow interaction for tripped nozzle and three swirling jet stream nozzles on the impingement wall at three different angles and Reynolds numbers

Experimental Facilities



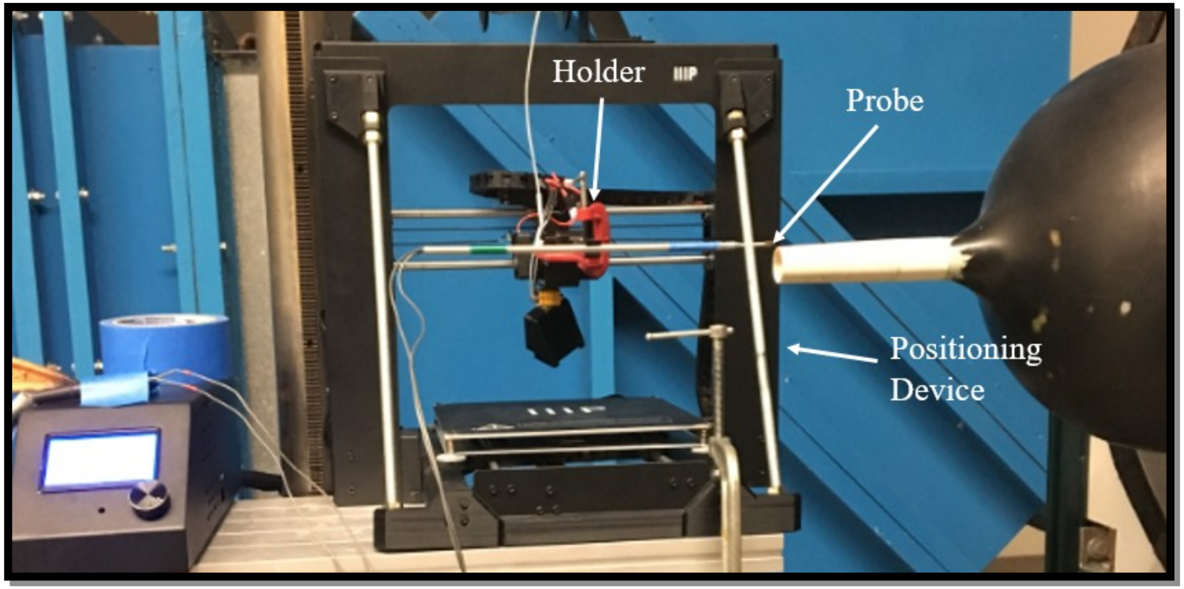
Facility jet system; Micro Air Vehicles Laboratory, AME Building, University of Arizona



Schematic of jet system

Hot Wire Measurement Technique

- Axial and azimuthal measurements taken for 1 second at 1kHz sample rate along the centerline of the nozzle at discrete location 2mm apart.
- Each data set was averaged to give a single data point for the discrete location



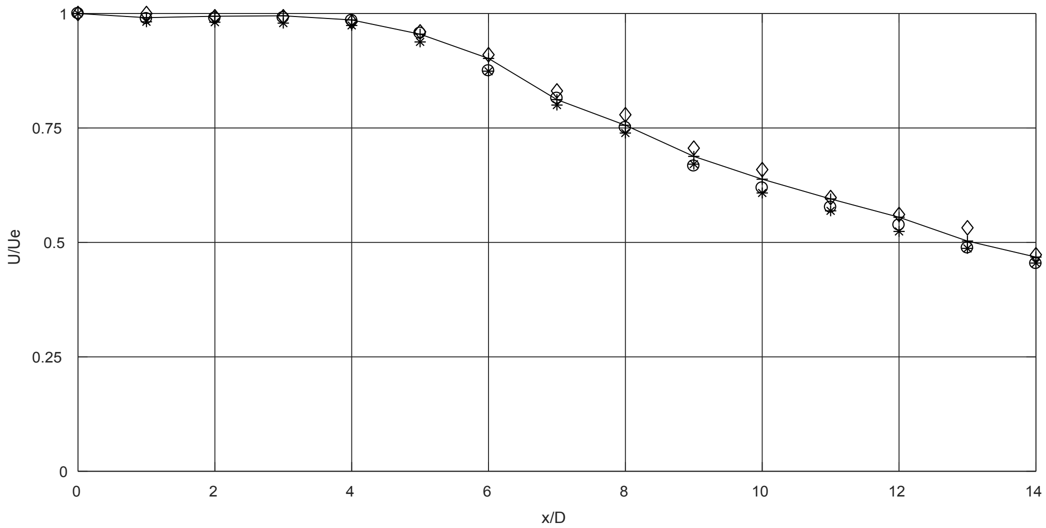
Hot Wire Measurement Setup

Tripped Nozzle Experiment

Boundary lay trip ring 3D printed and installed in nozzle at 1” from exit

- PLA Model 100% infill
- 0.140″ length and .020″ thick with four axial notches [6]
- Axial jet stream profile measured at 5 stations spaced two inch apart; Centerline profile measured to 15*D*
- Measured for four Reynolds numbers , 6.2×10^4, 8.30×10^4, 1.02×10^5, 1.24×10^5

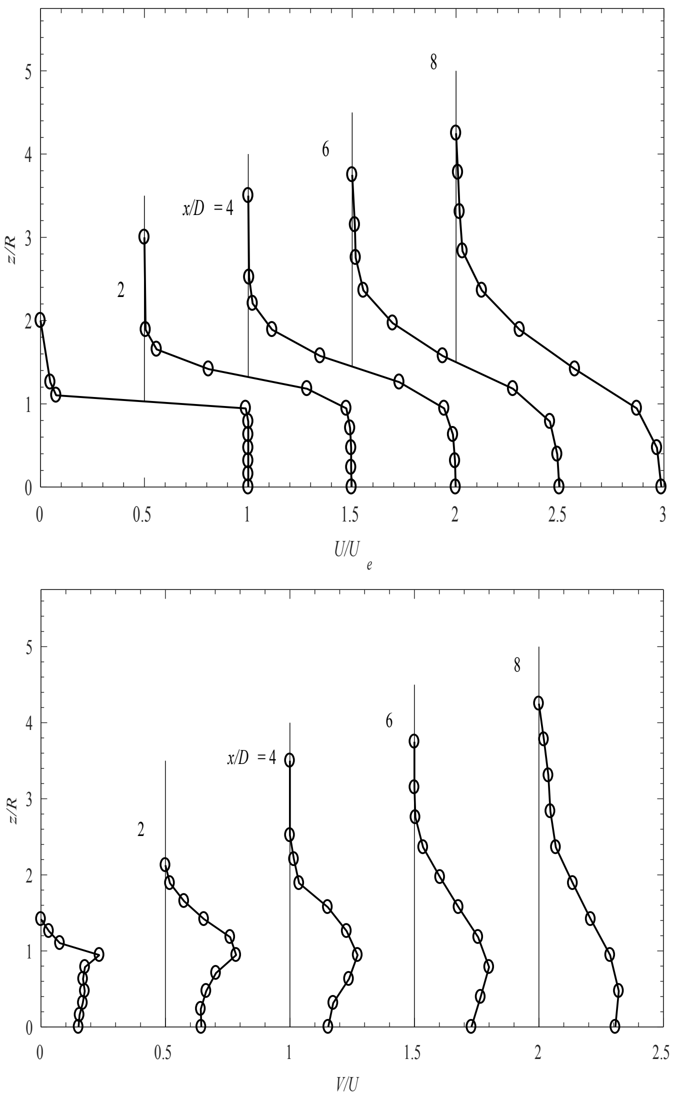
Tripped Nozzle Mean Axial Speed on the Centerline



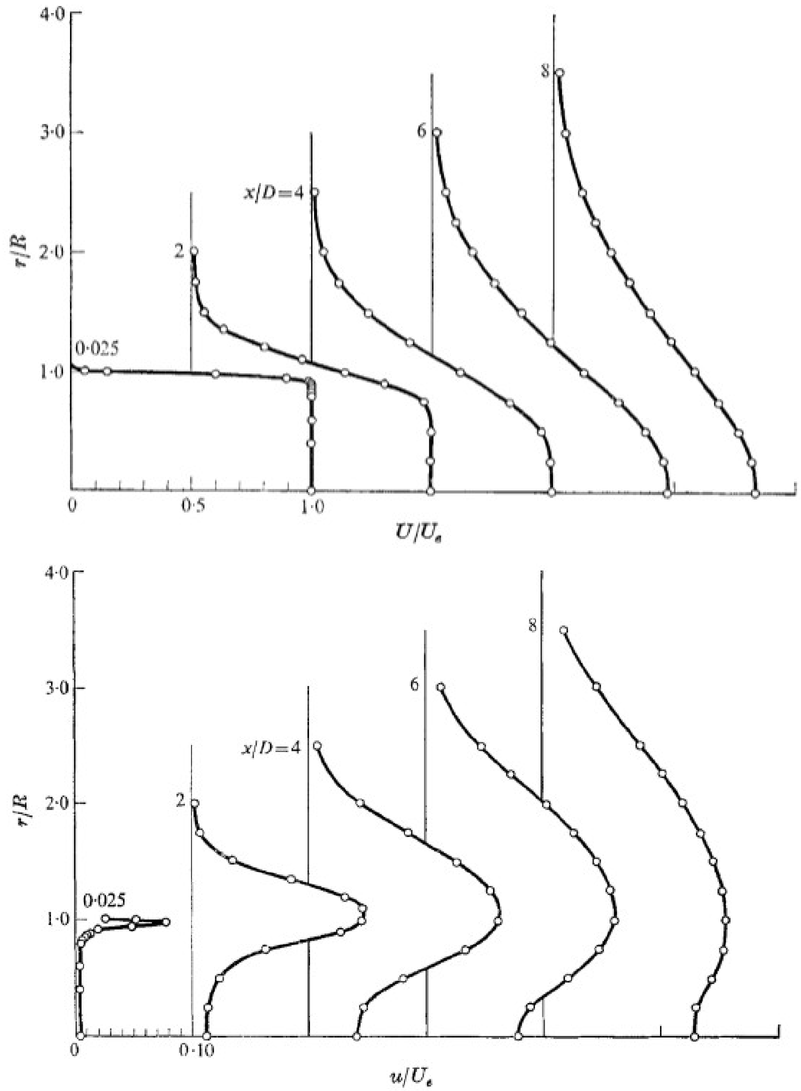
Profile of the mean axial speed on the centerline at several Reynolds numbers, as denoted by the following data symbols: ◊, 6.2 x 104; +, 8.30 x 104; ○, 1.02 x 105; *, 1.24 x 105, --, [6].

- Centerline profile does not change with Re
- Compares closely to pervious research [6]

Axial and Azimuthal Profile

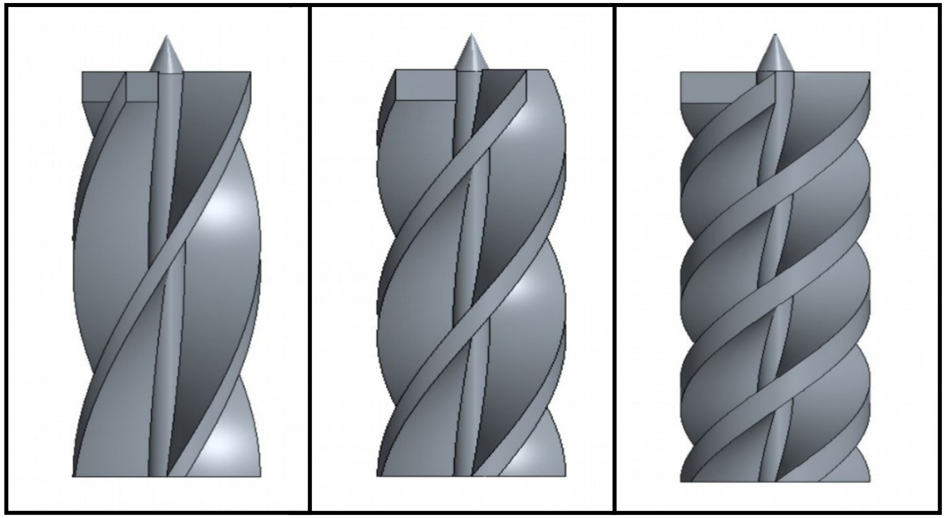


Measured profiles from blower



Profiles from previous research [6]

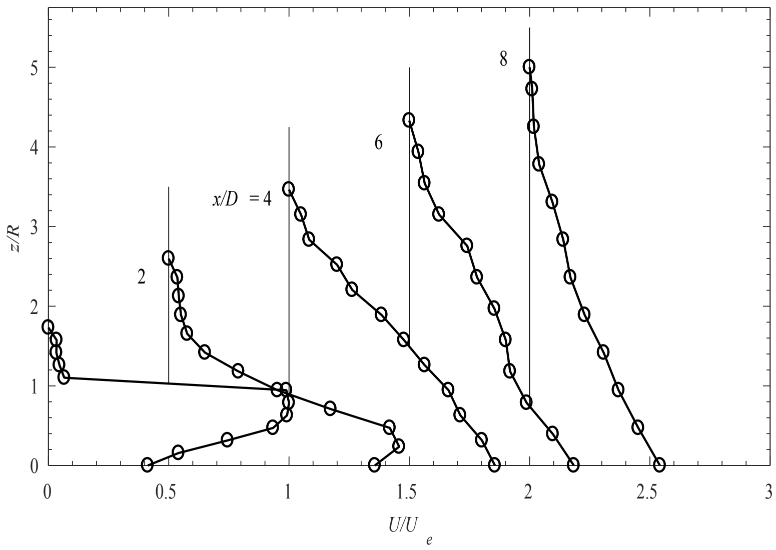
Swirling Nozzle Characterization



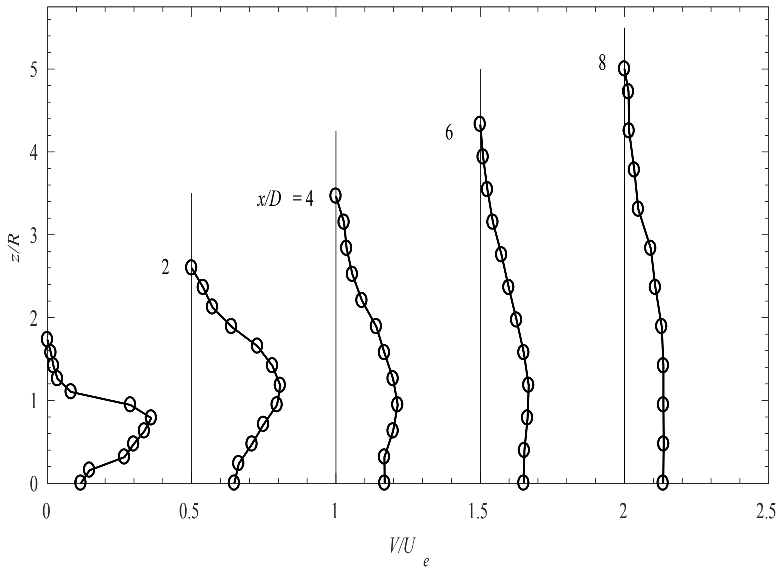
Interior of 3D printed Swirling Jet Steam Nozzles

- PLA Model 100% infill
- Nozzle's blades were swept at 3.00", 5.00" and 7.00" pitch
- Axial jet stream profile measured at 5 stations spaced two inch apart;
- Measured at Reynolds number 6.2×10^4

Nozzle 3 Axial and Azimuthal Profile



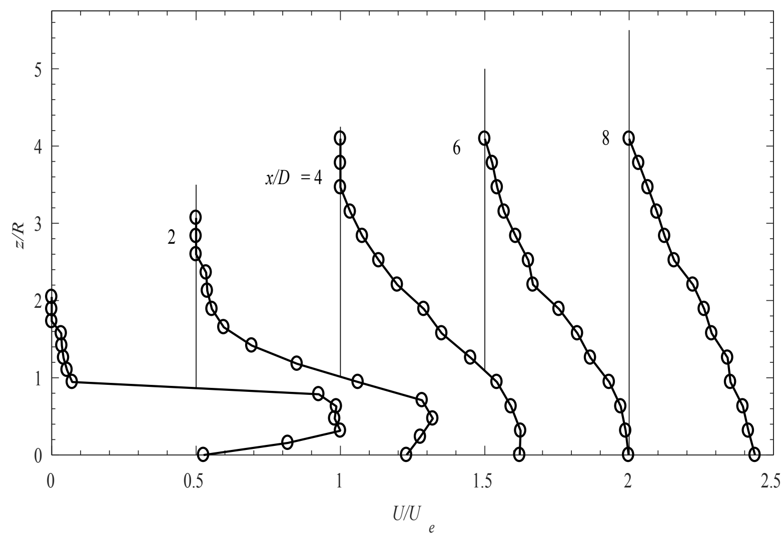
Axial Profile



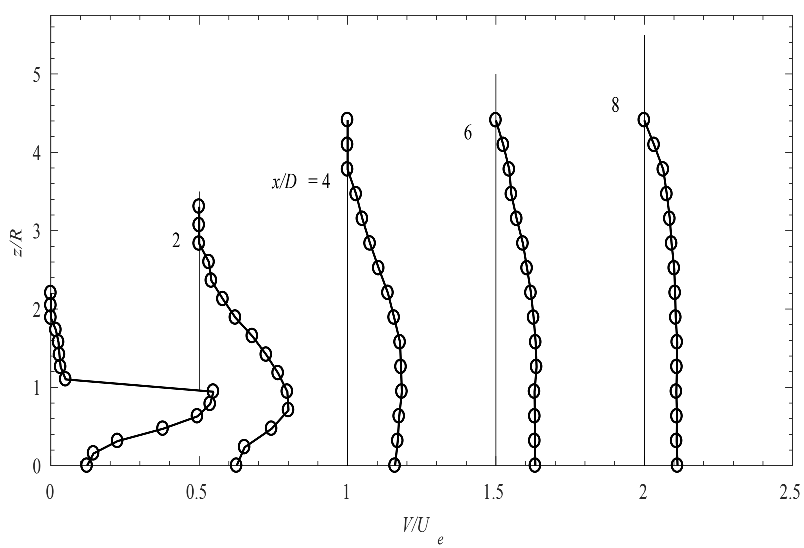
Azimuthal Profile

- Similar profile to tripped nozzle jet stream
- Axial become a conical shape
- Azimuthal profile dissipates quicker

Nozzle 5 Axial and Azimuthal Profile



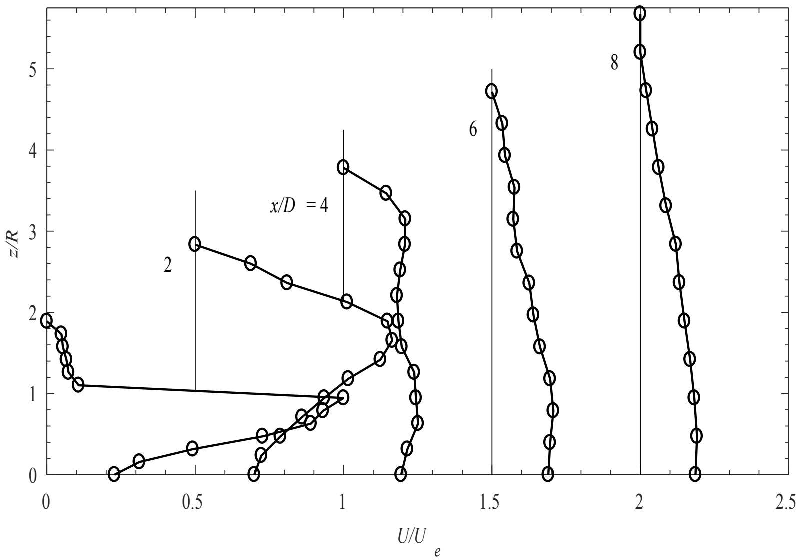
Axial Profile



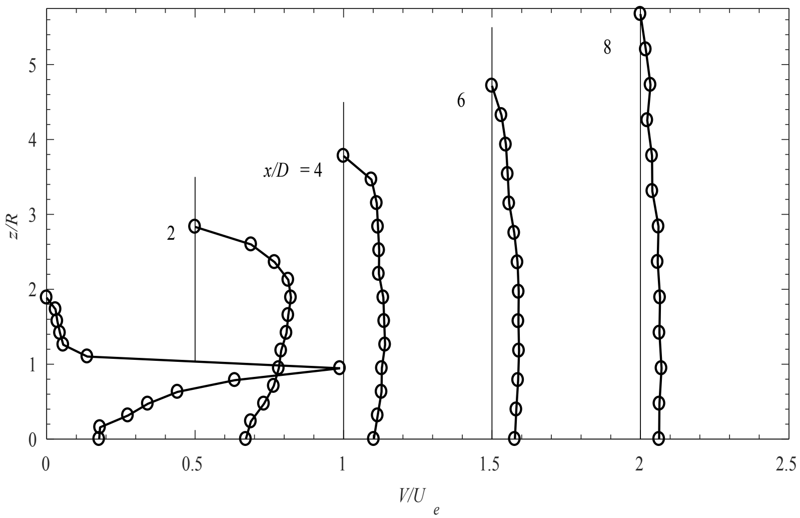
Azimuthal Profile

- Similar profile to nozzle 3 jet stream
- There is less of an axial component then nozzle 3
- Azimuthal profile is stronger at the first two stations

Nozzle 7 Axial and Azimuthal Profile



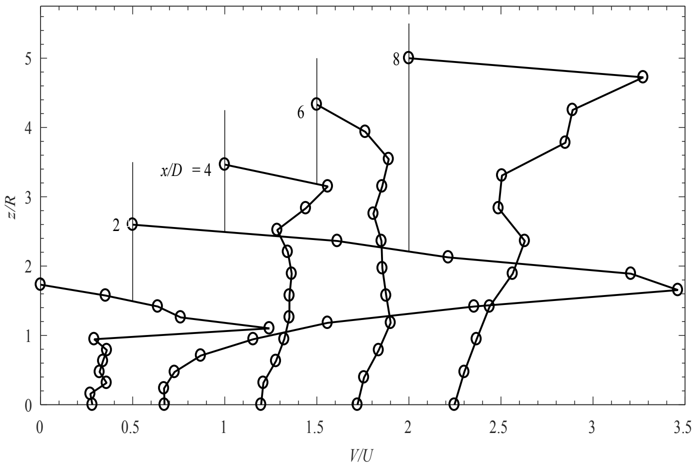
Axial Profile



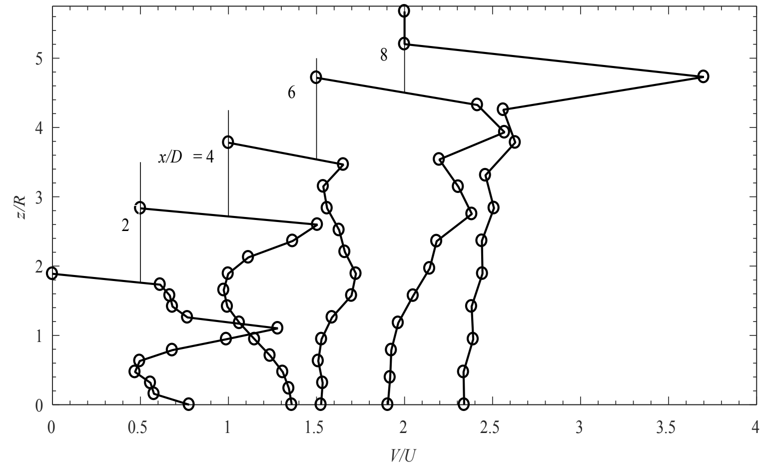
Azimuthal Profile

- Irregular axial profile
- Axial profile resembles the azimuthal profile for nozzle 5
- Azimuthal profile is strongest at the first two stations

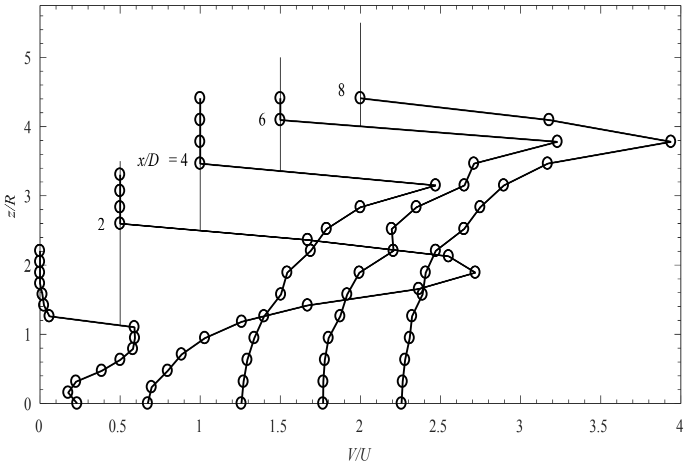
Swirling Intensity Profiles



Nozzle 3



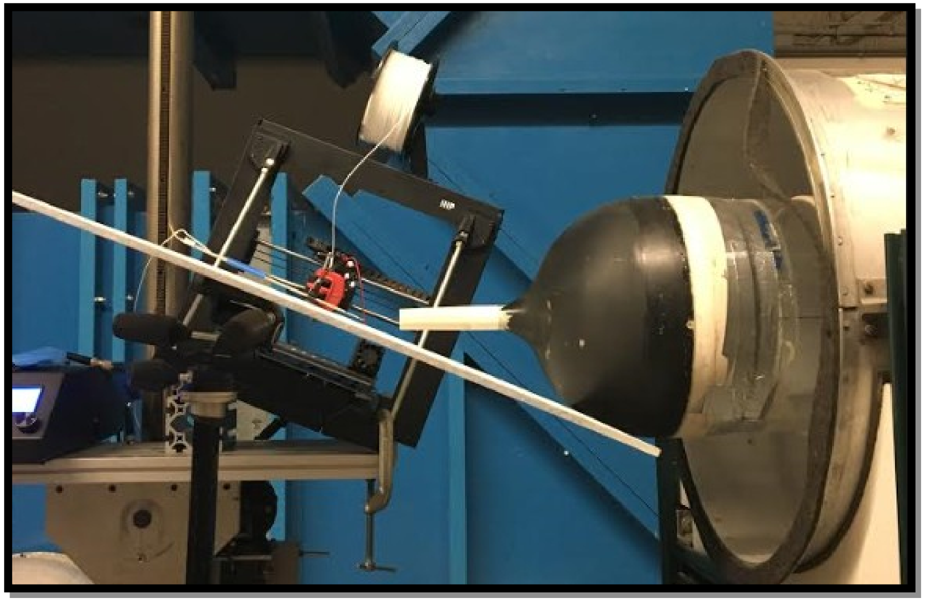
Nozzle 7



Nozzle 5

Nozzle Reference Name	Mechanical Swirl (Pitch)	Swirl Number
Nozzle 3	3.00”	0.31
Nozzle 5	5.00”	0.59
Nozzle 7	7.00”	0.71

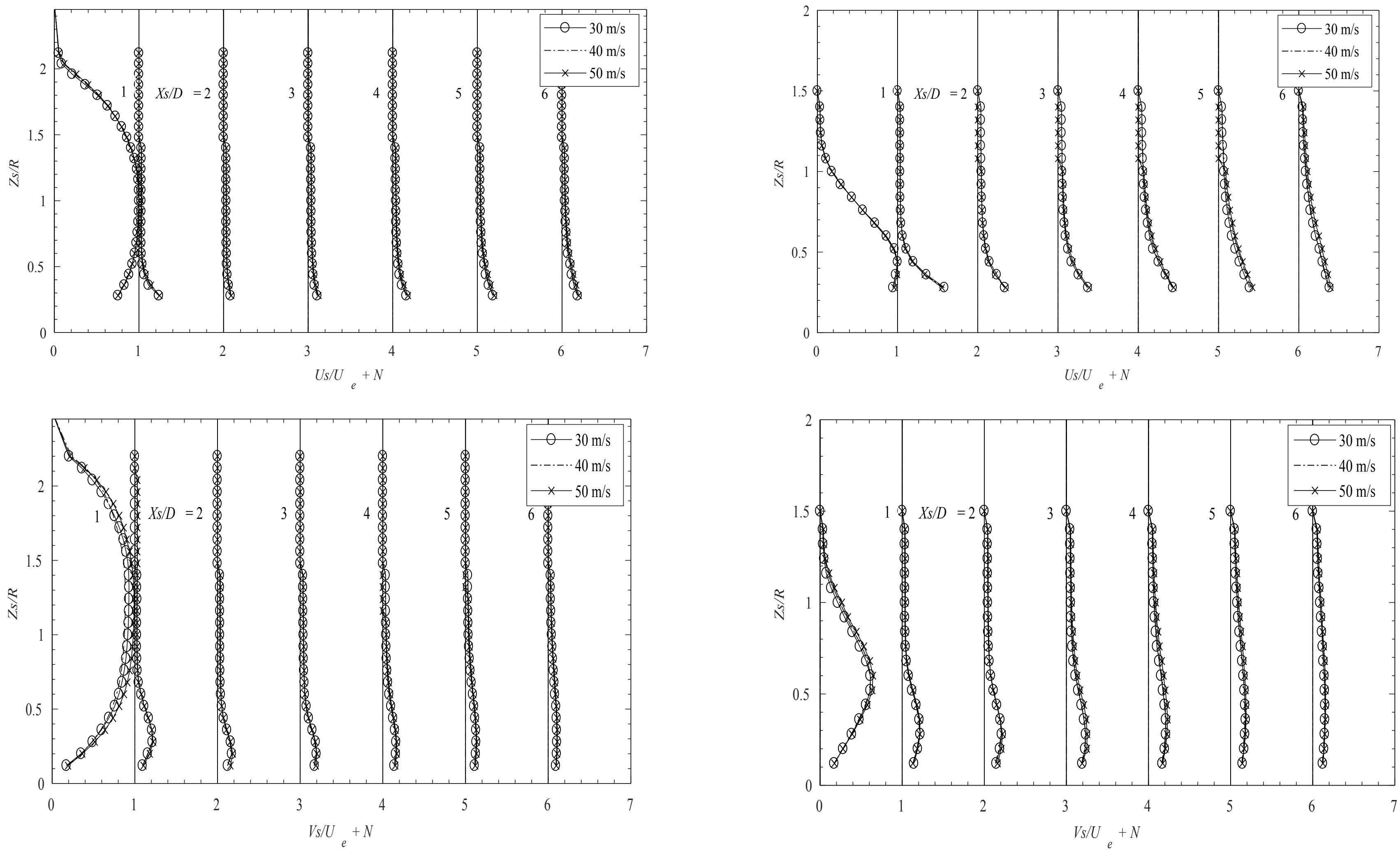
Tripped Jet on Impingement Surface



Hot Wire Impingement Setup

- Distance from nozzle to impingement wall (*d*) = 2.00”
- Impingement wall set to three angles of θ: 22.5°, 45° & 67.5°
- Axial and azimuthal jet stream profile measured at 7 stations spaced two inch apart;
- Measured for three Reynolds numbers , 4.21×10^4, 5.6×10^4, 7.02×10^4

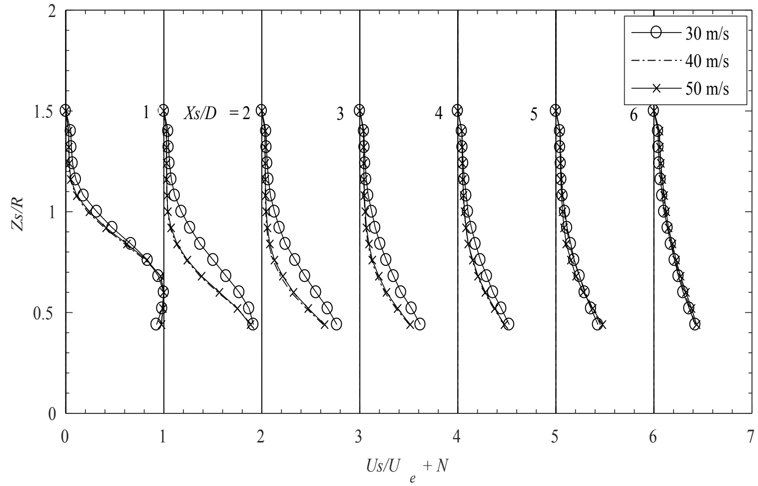
Tripped Nozzle Velocity Comparison

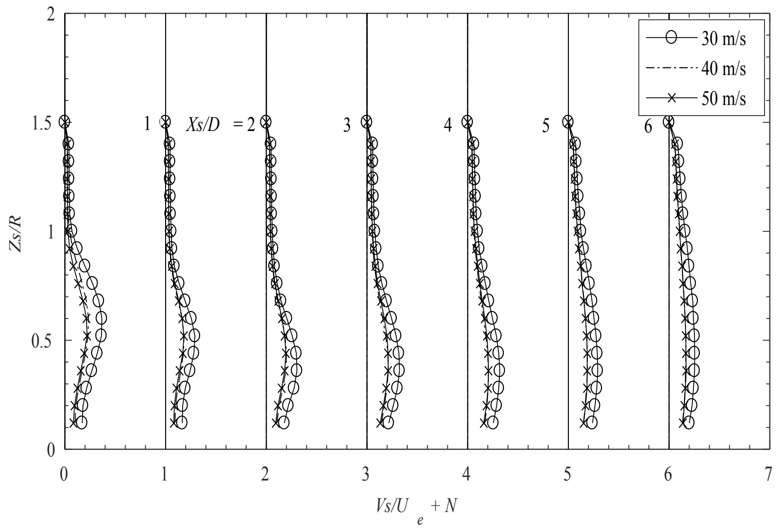


22.5° Axial and Azimuthal Profiles

45° Axial and Azimuthal Profiles

Tripped Nozzle Velocity Comparison

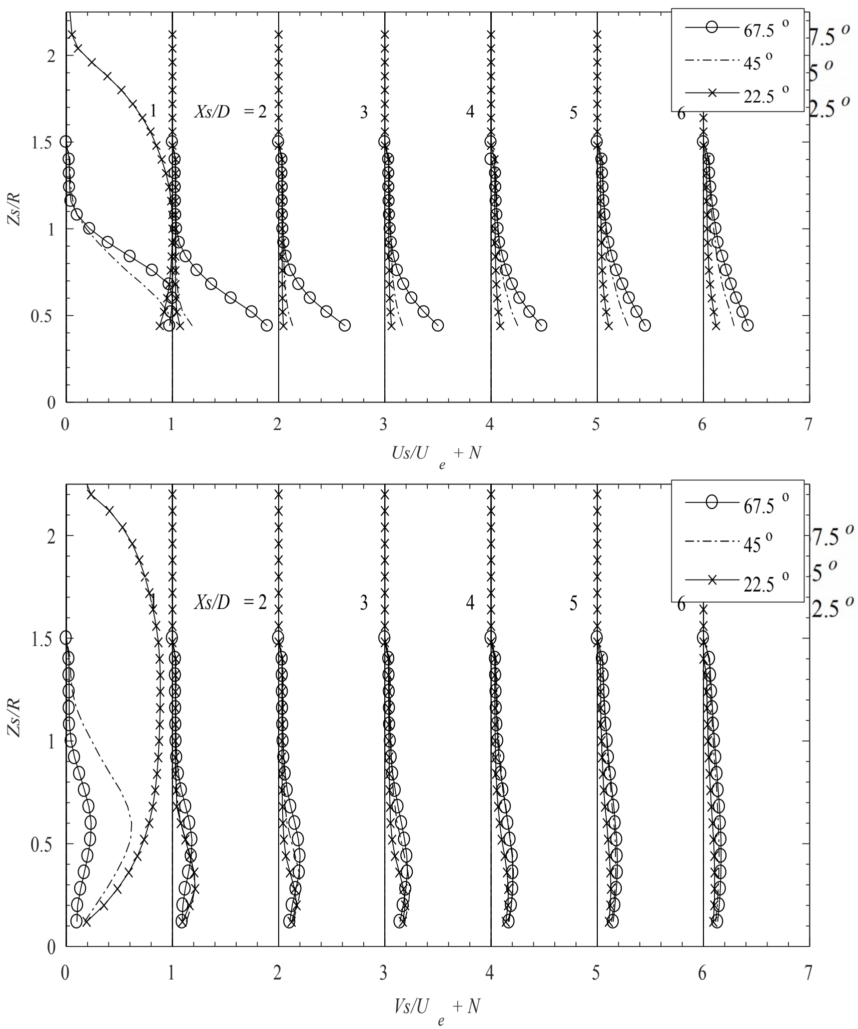




67.5° Axial and Azimuthal Profiles

- Change in velocity does not influence the jet stream profile
- One outlier case of 50m/s at θ = 67.5°
- Expected result because unimpeded flow shows similar characteristics

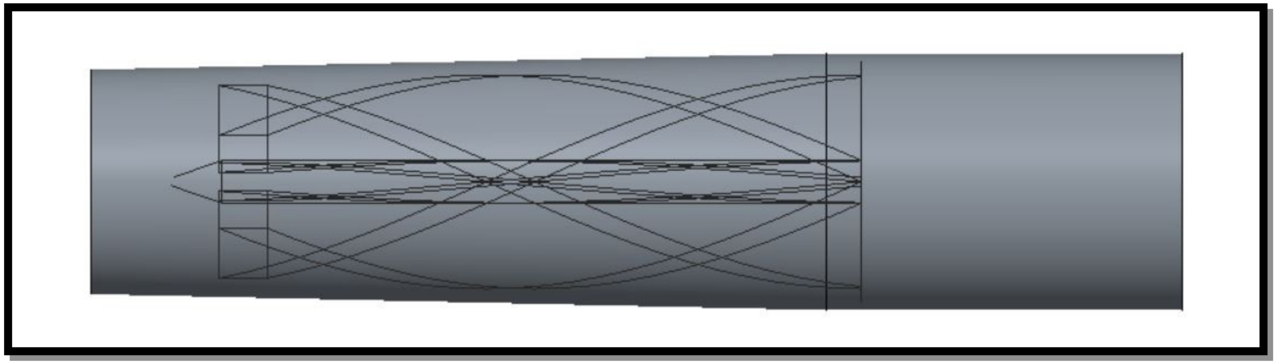
Tripped Nozzle Angle Comparison



40 m/s Axial and Azimuthal Profiles

- Axial profiles differ greatly between setups
  - θ = 22.5° dissipates quickly
  - θ = 45° mildly effected by impingement wall
  - θ = 67.5° nearly uneffected by impedance
- Besides station $x = 0$ there is little change in the azimuthal profile
- Sufficient dissipation will be classified as a reduction in axial or azimuthal velocity by 50% before reaching station 2

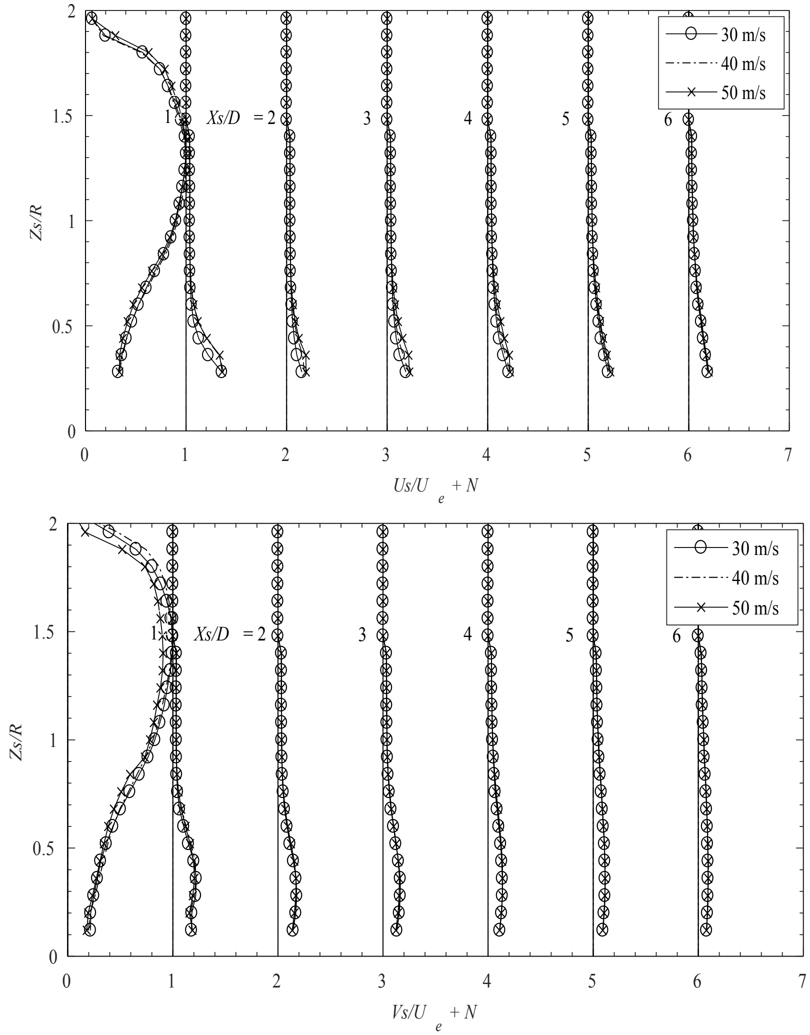
Swirling Jet on Impingement Surface



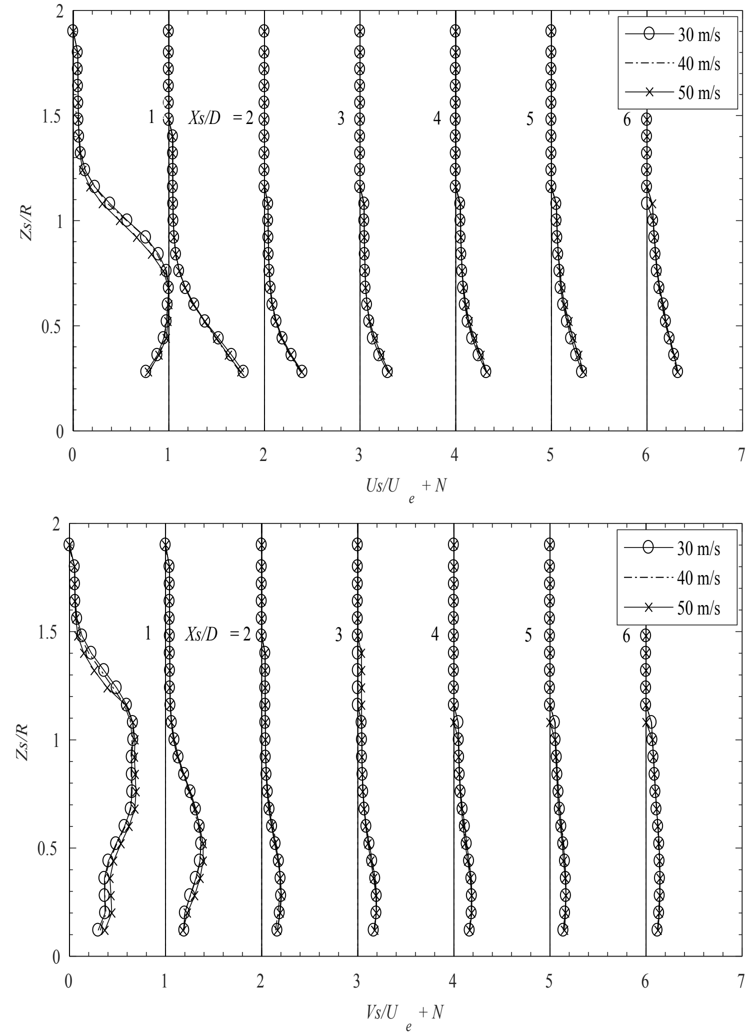
Swirling Jet Stream Nozzle

- Three swirling nozzles; 3″, 5″ & 7″ pitch
- Distance from nozzle to impingement wall (*d*) = 2.00″
- Impingement wall set to three angles of θ: 22.5°, 45° & 67.5°
- Axial and azimuthal jet stream profile measured at 7 stations spaced two inch apart;
- Measured for three Reynolds numbers , 4.21 x 10^4, 5.6 x 10^4, 7.02 x 10^4

Nozzle 3 Velocity Comparison

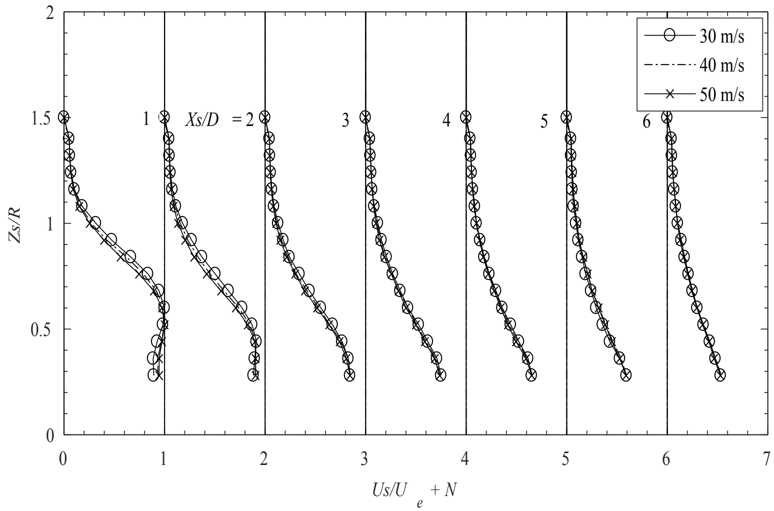


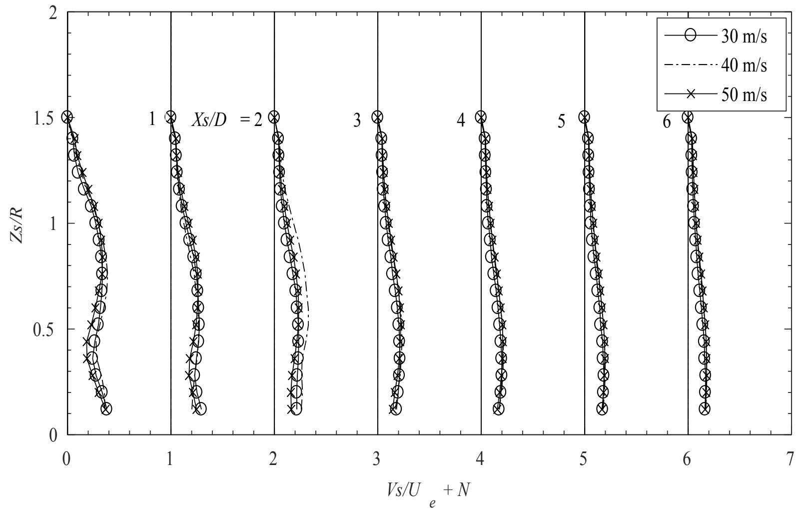
22.5° Axial and Azimuthal Profiles



45° Axial and Azimuthal Profiles

Nozzle 3 Velocity Comparison

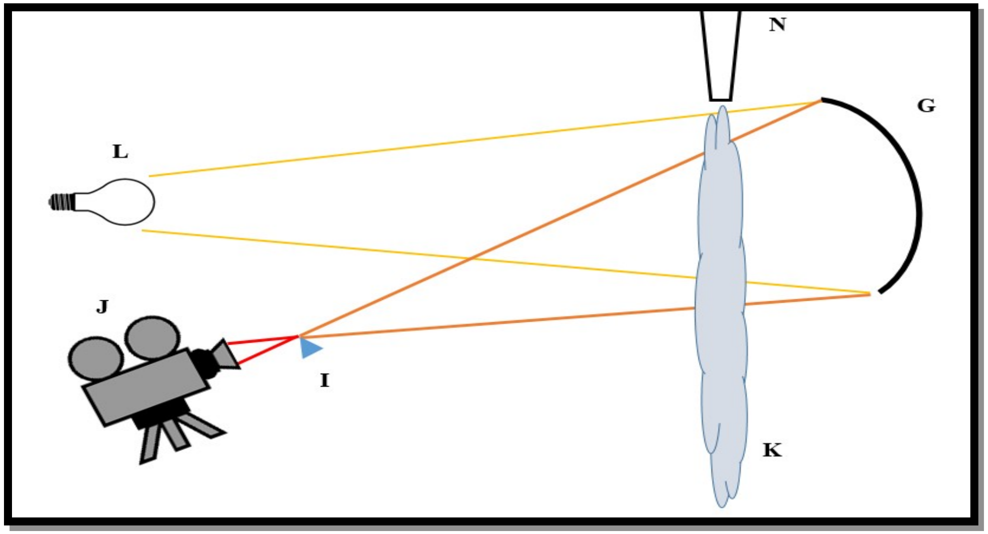




67.5° Axial and Azimuthal Profiles

- Change in velocity does not influence the jet stream profile
- No significant outliers for Nozzle 3
- Nozzles 5 and 7 did have a few outliers like the tripped nozzle

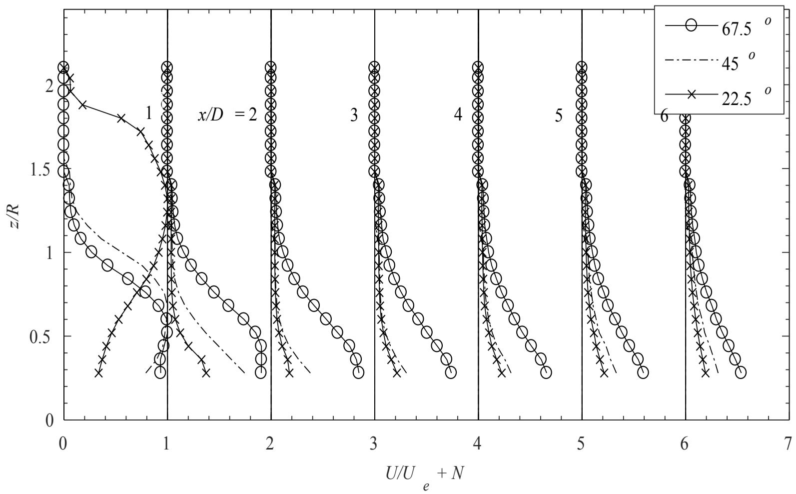
Schlieren Images and Video

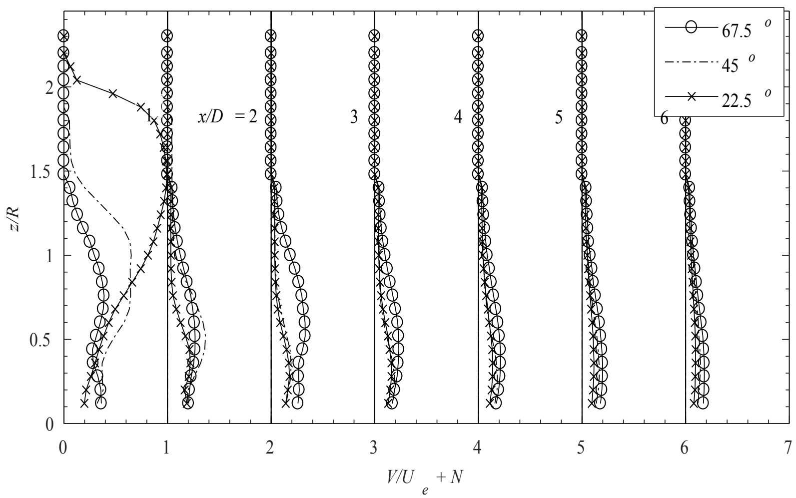


Swirling Jet Stream Nozzle

- Three swirling nozzles; 3″, 5″ & 7″ pitch
- Distance from nozzle to impingement wall (*d*) = 2.00″
- Impingement wall set to three angles of *θ*: 22.5°, 45° & 67.5°
- Axial jet stream profile captured
- Measured for three Reynolds number 5.6 x 10^4
- CO_2 seeding at 30psi, approximately a 50% increase in density

Nozzle 3 Angle Comparison

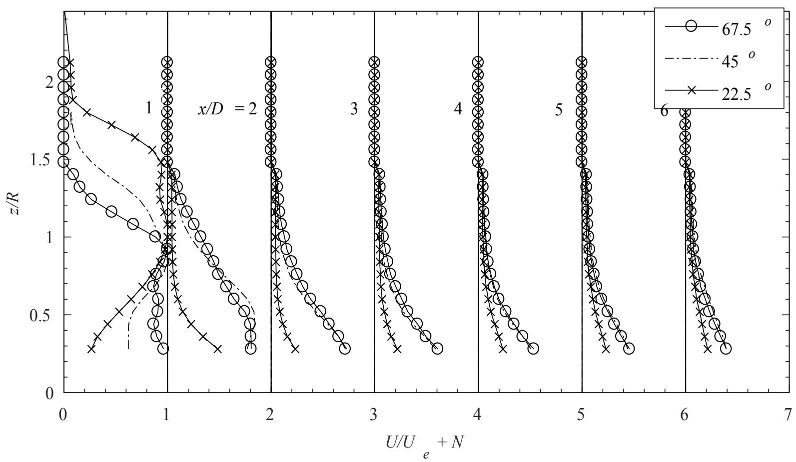


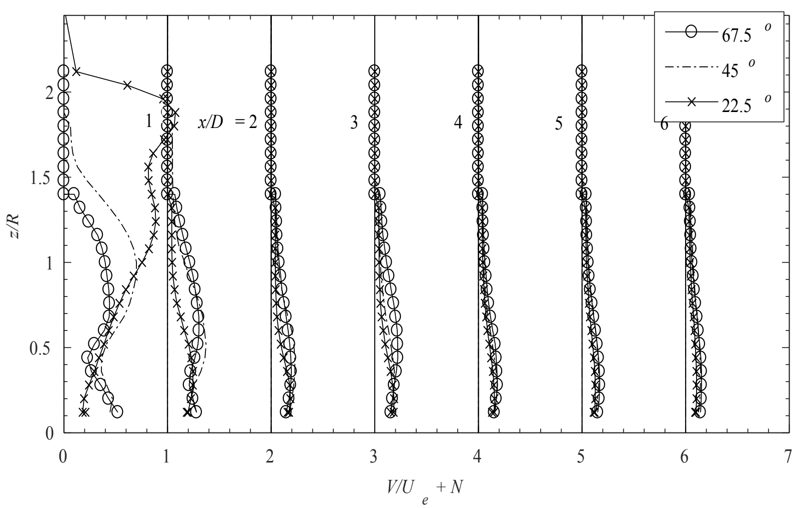


40 m/s Axial and Azimuthal Profiles

- Axial profiles differ greatly between setups
  - θ = 22.5° dissipates quickly
  - θ = 45° slows down but at half the rate of 22.5°
  - θ = 67.5° nearly unaffected by impedance
- Azimuthal profile differ greatly at *x/D* = 0
  - θ = 22.5° dissipates quickly
  - θ = 45° slows down but at half the rate of 22.5°
  - θ = 67.5° effected but takes four times as long than 22.5°

Nozzle 5 Angle Comparison

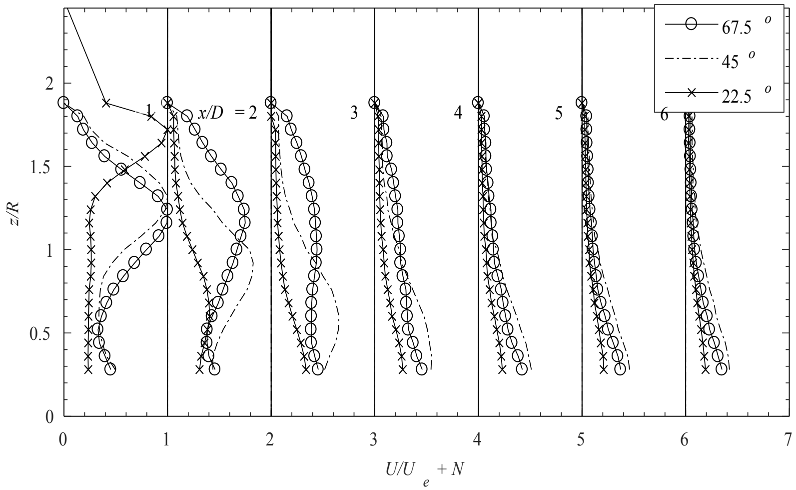


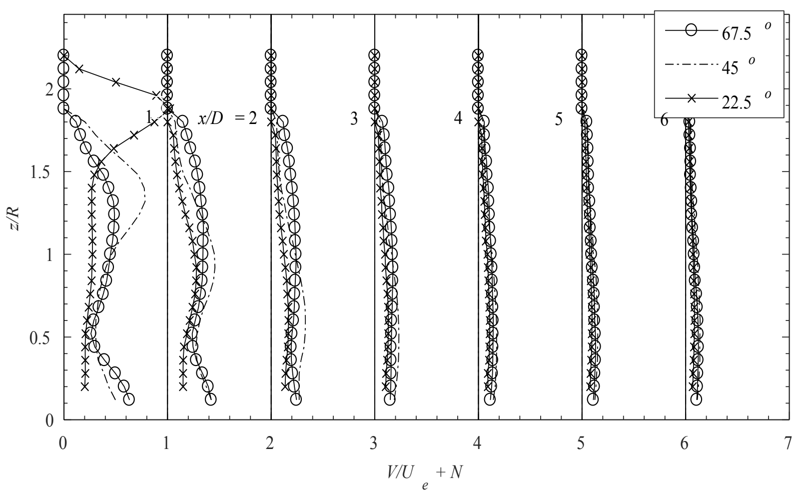


40 m/s Axial and Azimuthal Profiles

- Axial profiles differ greatly between setups
  - θ = 22.5° dissipates quickly
  - θ = 45° & 67.5° slows at about the same rate
  - Impingement surface is no at as effective on the Nozzle 5 axial profile
- Azimuthal profile differ greatly at $x/D = 0$
  - θ = 22.5° dissipates quickly
  - θ = 45° slows down but at half the rate of 22.5°
  - θ = 67.5° effected but takes four times as long than 22.5°

Nozzle 7 Angle Comparison

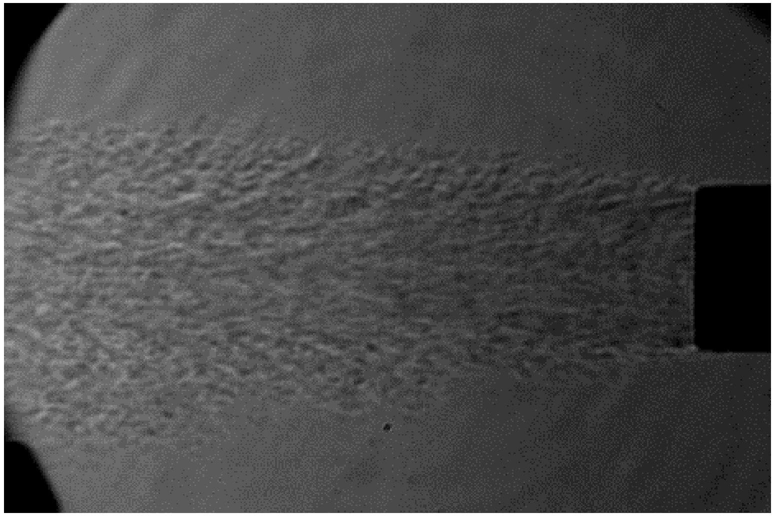




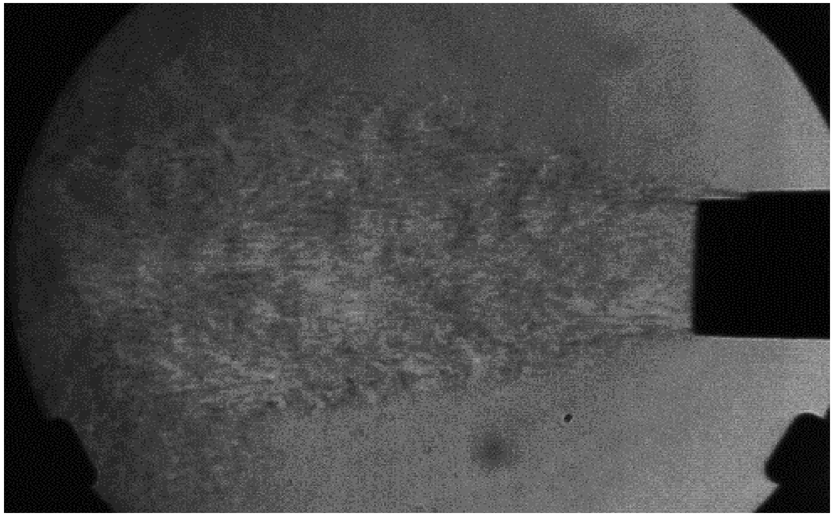
40 m/s Axial and Azimuthal Profiles

- Axial profiles differ greatly between setups
  - θ = 22.5° dissipates quickest
  - θ = 45° & 67.5° slows at about the same rate
  - Impingement surface least effective on the Nozzle 7 axial profile
- Azimuthal profile differ greatly at x/D = 0
  - θ = 22.5° dissipates quickly
  - θ = 45° slows down but at half the rate of 22.5°
  - θ = 67.5° effected but takes four times as long than 22.5°

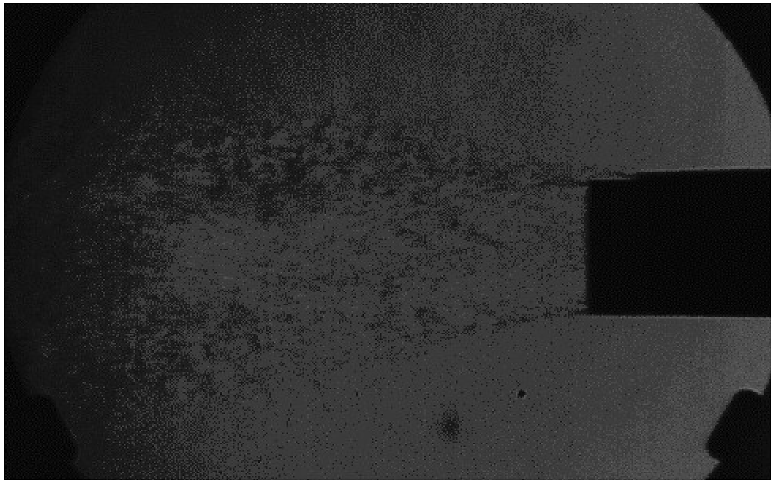
Unimpeded Schlieren Images



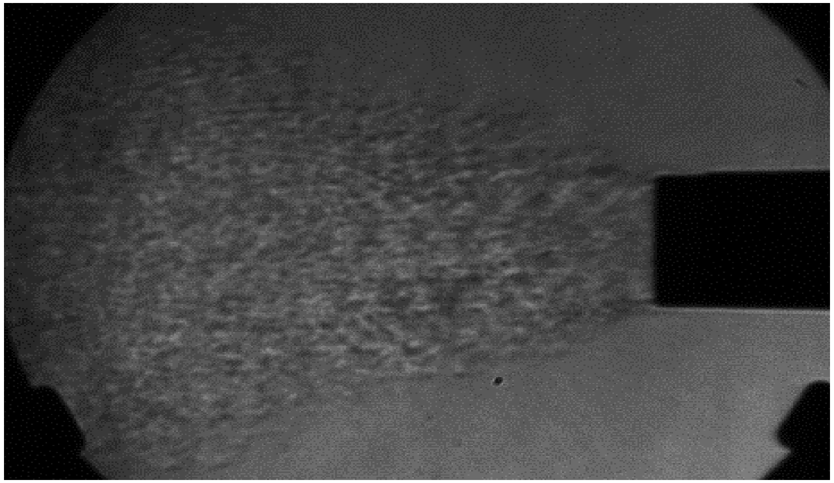
Tripped Nozzle



Nozzle 5

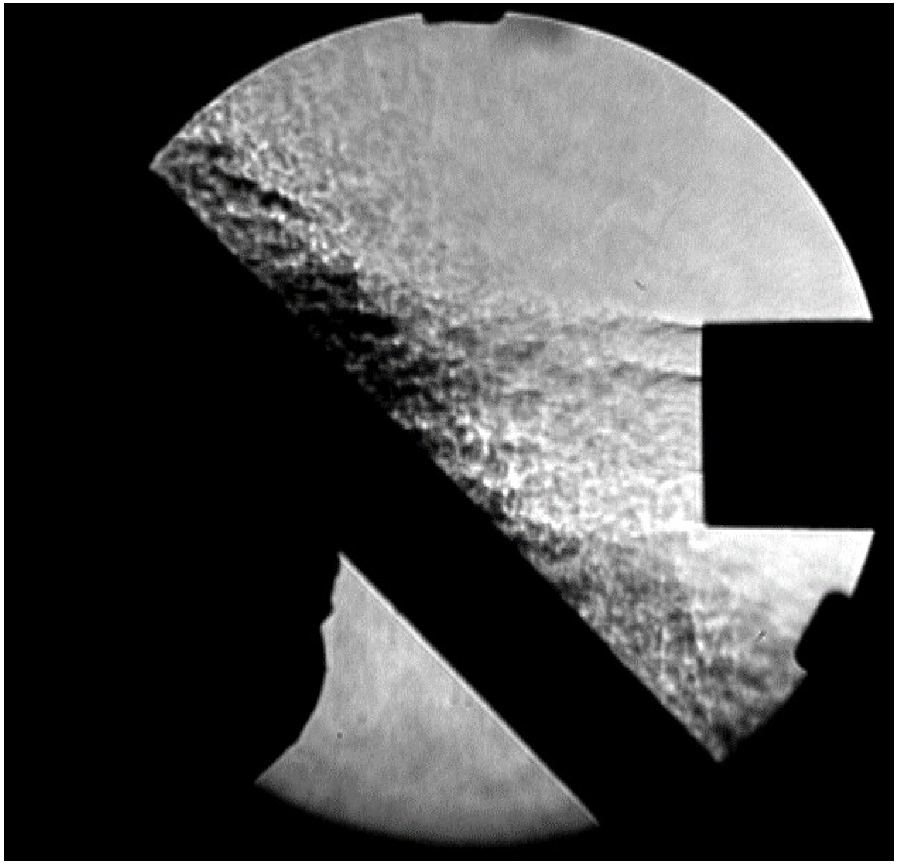


Nozzle 3



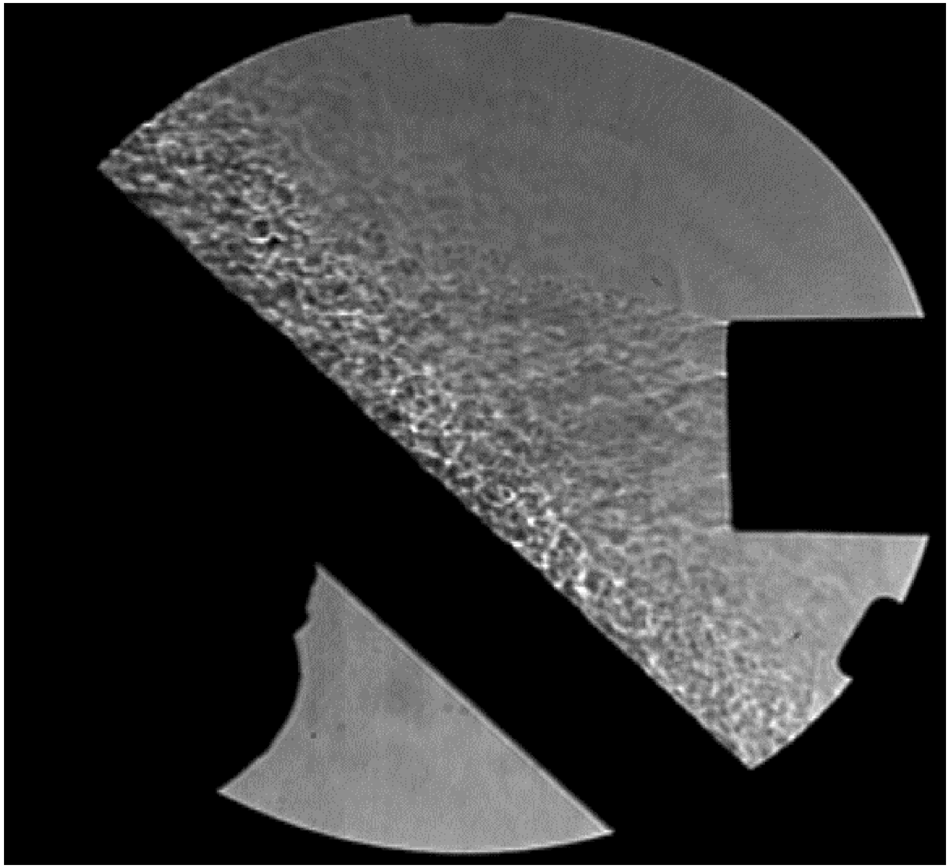
Nozzle 7

Schlieren Video



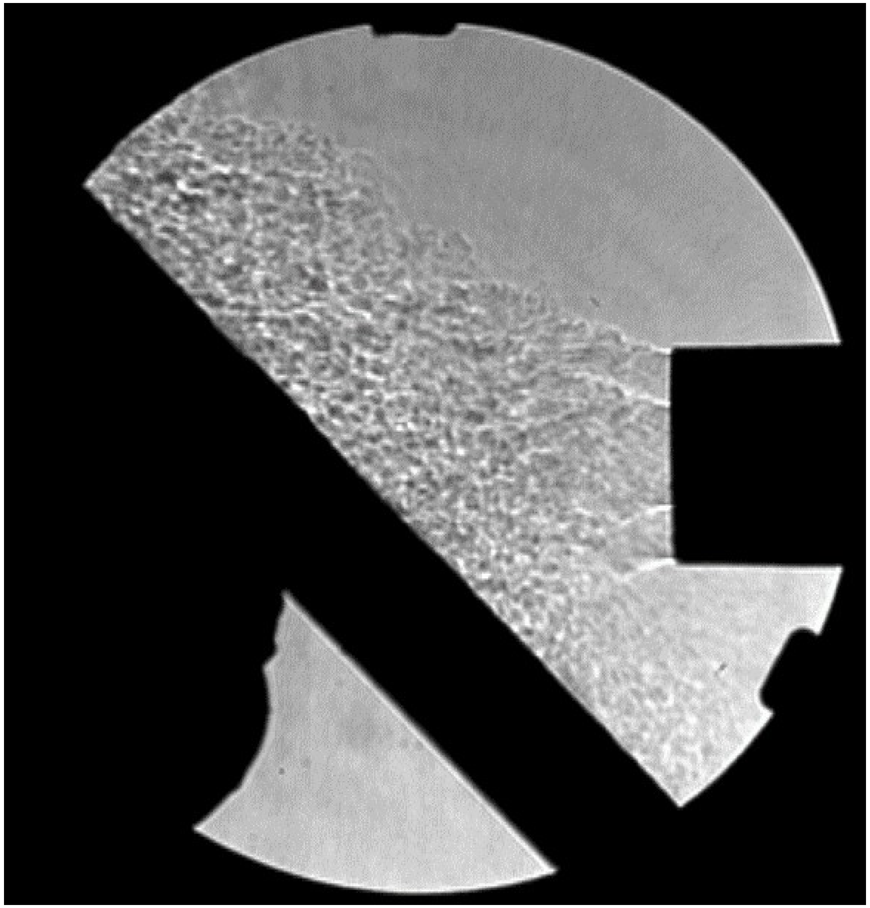
- Nozzle 3 with impingement wall at 45º
- Vortex below centerline

Schlieren Video



- Nozzle 5 with impingement wall at 45º
- Small vortex below centerline

Schlieren Video



- Nozzle 7 with impingement wall at 45º
- Azimuthal vortex above centerline

Summary of Results

- Angle required to dissipate jet stream flow increases as swirl number increases
- Required angle to effectively dissipate jet stream
  - $S = 0.31$; $\theta < 67.5^{\circ}$
  - $S = 0.59$; $\theta \leq 45^{\circ}$
  - $S = 0.71$; $\theta < 45^{\circ}$
- Azimuthal vortex formed when swirling jet stream was impinging on wall with $\theta \geq 45^{\circ}$ and $S = 0.71$
- Axial vortex formed below nozzle centerline when swirling jet stream was impinging on wall with $\theta \geq 45^{\circ}$ and $S \leq 0.59$

Conclusions

- Reynolds number did significantly effect the vortex jet stream profile
- Dissipating vortex flow would require impingement walls to be set at high angles of attack to be effective
- Some interesting flow characteristics were observed for higher swirl number flows
  - Other forms of flow visualization could be used to better understand these behaviors such as oil field [2]

Questions?