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Control of Supersonic Impinging Jets Using Microjets

Huadong Lou

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Outline

- Motivation
- Mechanism
  - Feedback loop
  - Mechanism of microjet control
- Results and Discussion
- Conclusions

Motivation

JSF X-32B on the hover

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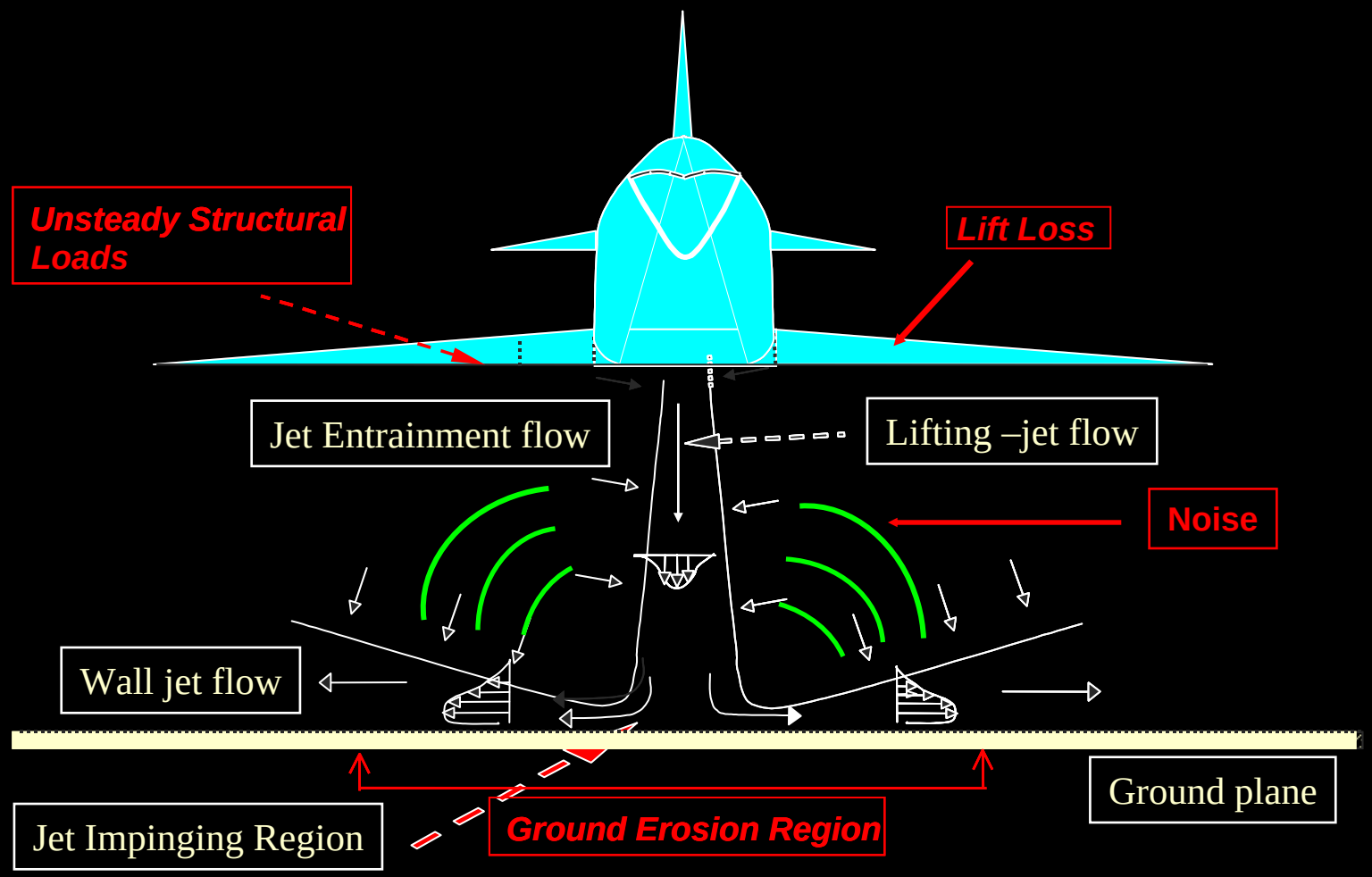
Motivation

Flow schematic for a jet STOVL aircraft in hover



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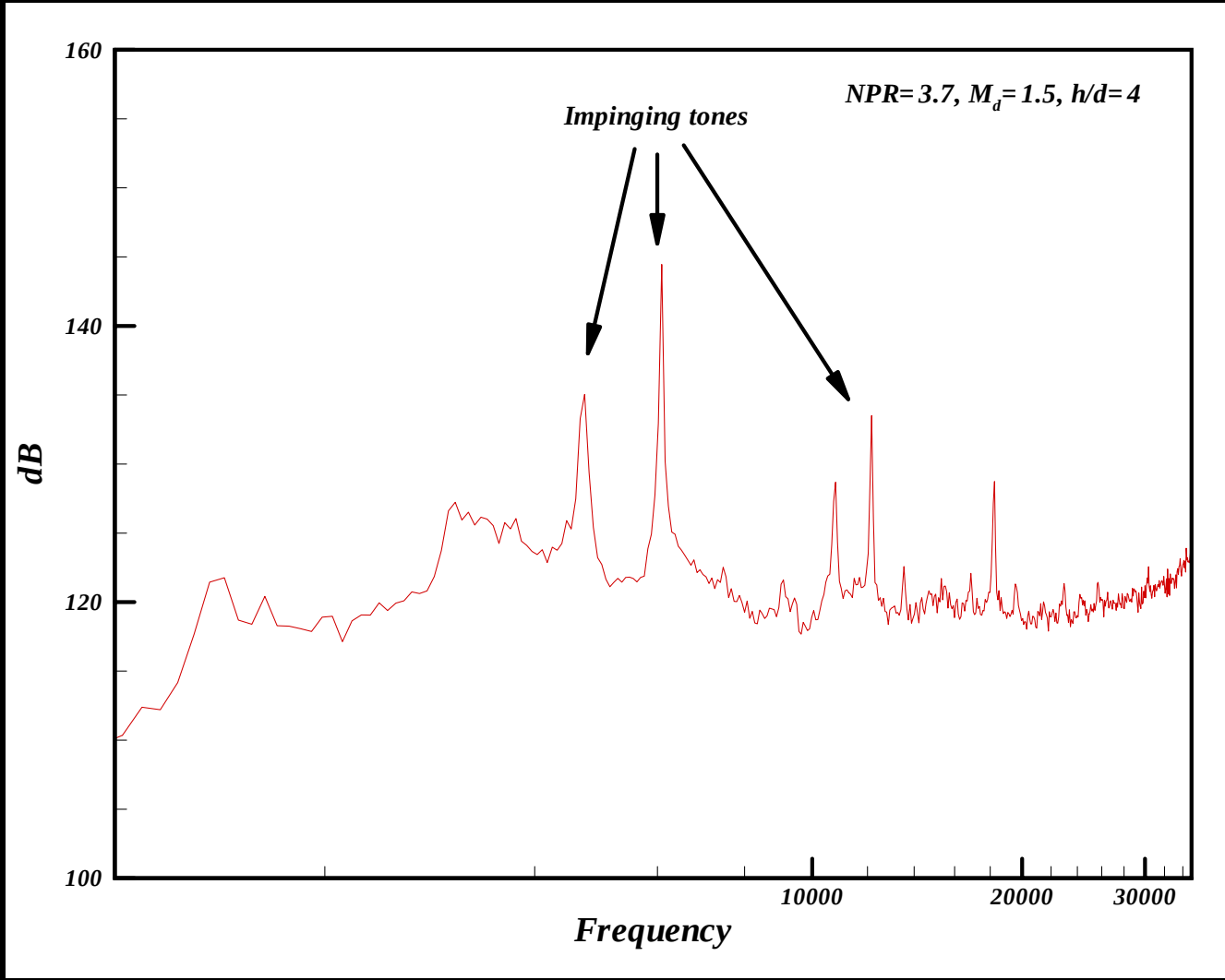
Motivation



Near field noise spectrum, NPR=3.7, h/d=4

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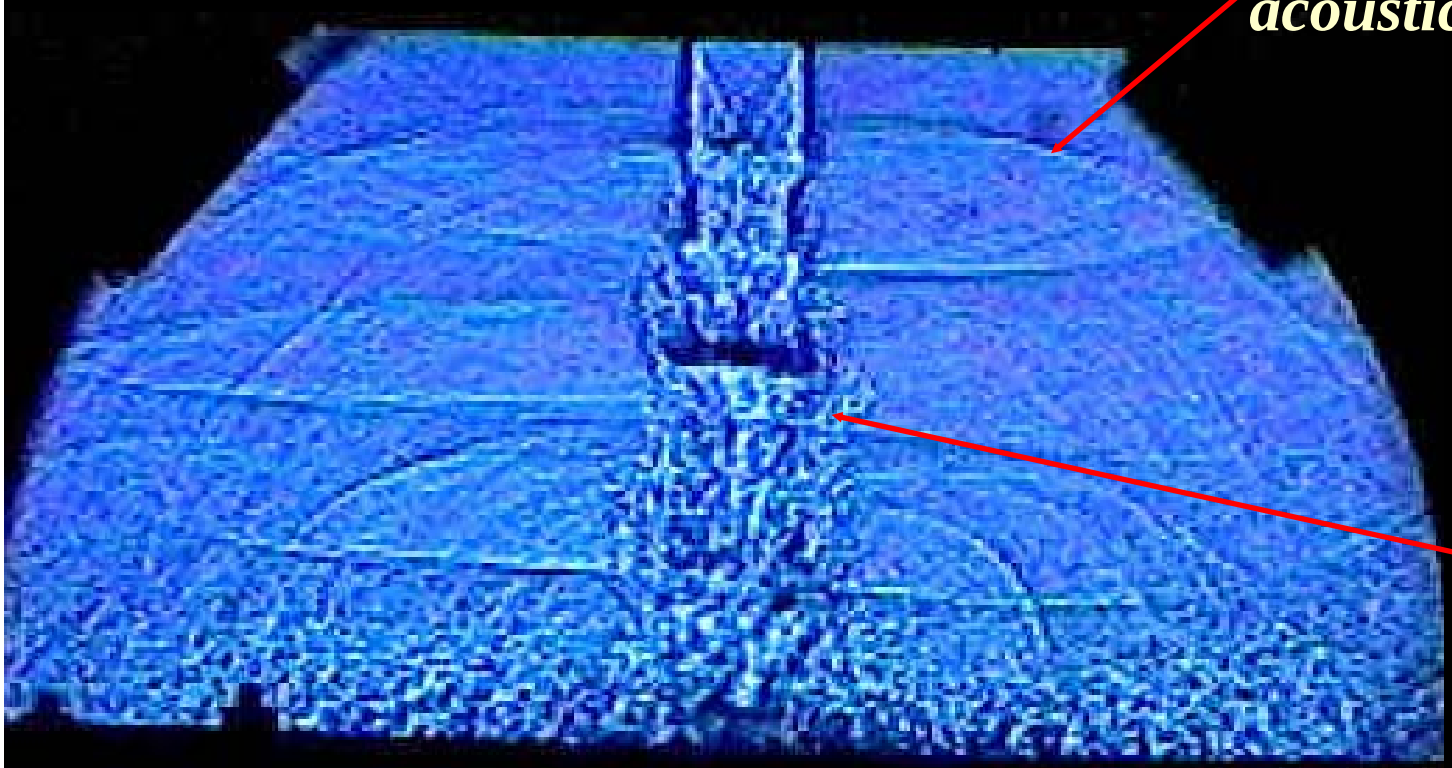
Mechanism

Feedback loop



Powell, Karamcheti, Tam & Ahuja, Krothapalli et al.

Goal

- **To understand the characteristics of supersonic impinging jet flow**

- **To actively and efficiently control the jet behavior by disrupting the feedback loop**
  - **Reduce: Tones, OASPL and other related adverse effects**

- **To understand the mechanism behind the microjets control method**

Prior Attempts at Feedback Control

- Karamcheti et al. (1969): Edge tone suppression using baffles/plates
- Samimy et al. (1993): Screech tone suppression using tabs
- Sheplak & Spina (1994): Impinging tone suppression via coflow
- Shih et al. (1999): Screech tone suppression using counterflow
- Elavarasan et al. (1999): Impinging tone suppression via baffles

Present Approach

- Use supersonic microjets to disrupt the feedback loop:
  - High momentum, low mass flow
  - Relatively simple, can be actively manipulated to provide optimal control

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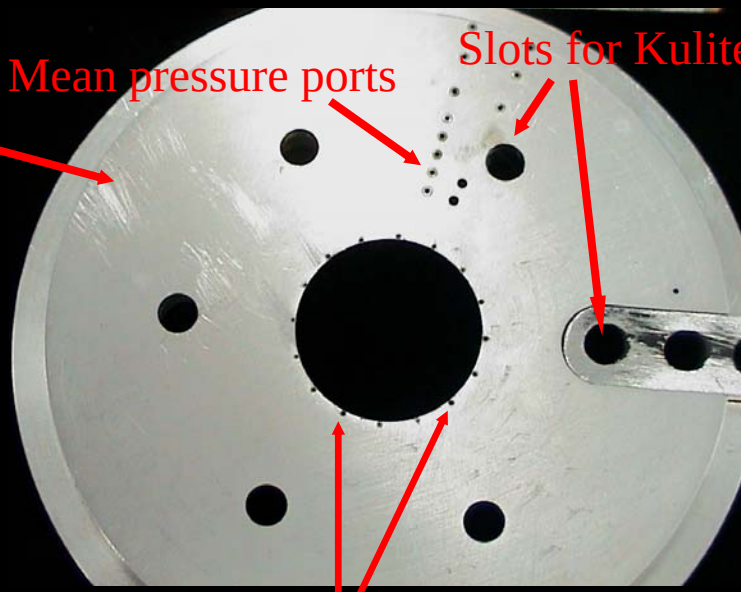
Test Model and Facility

Lift plate



Ground plate

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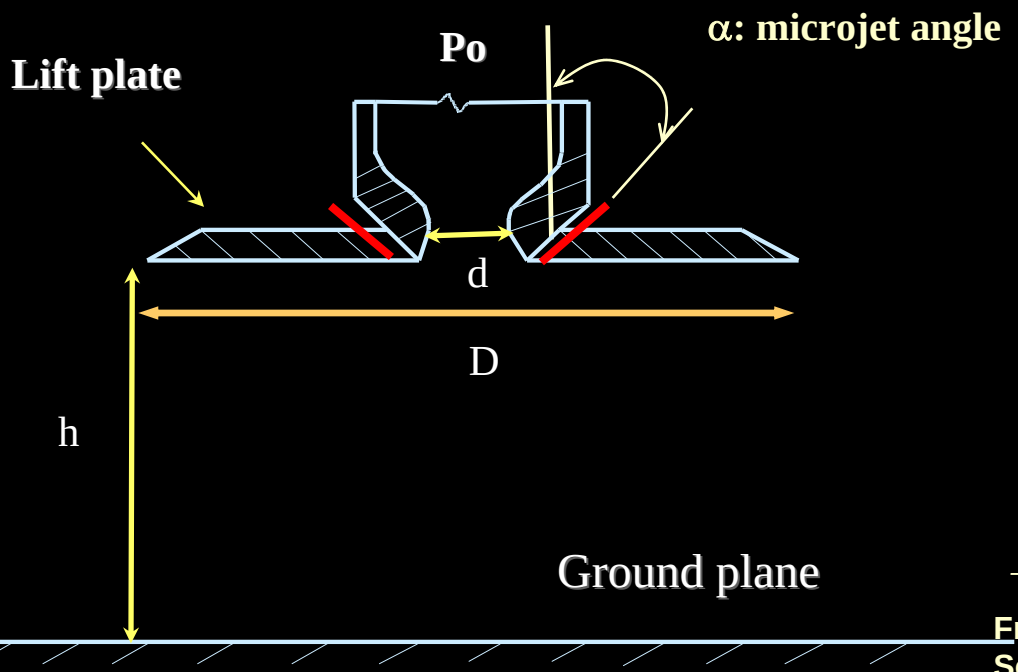
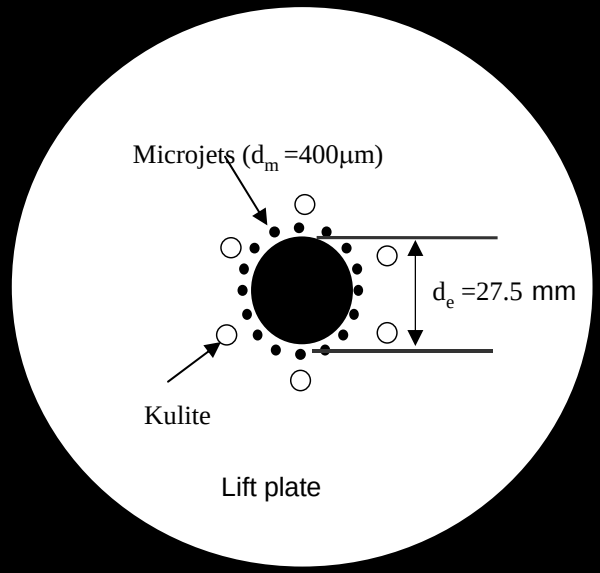
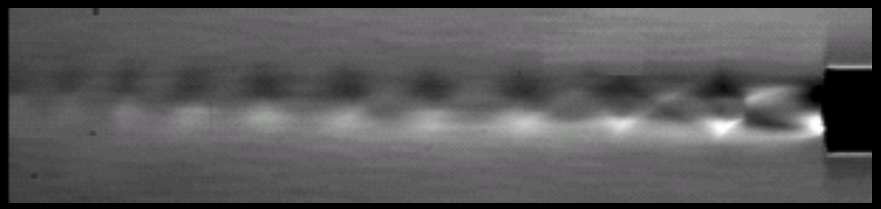
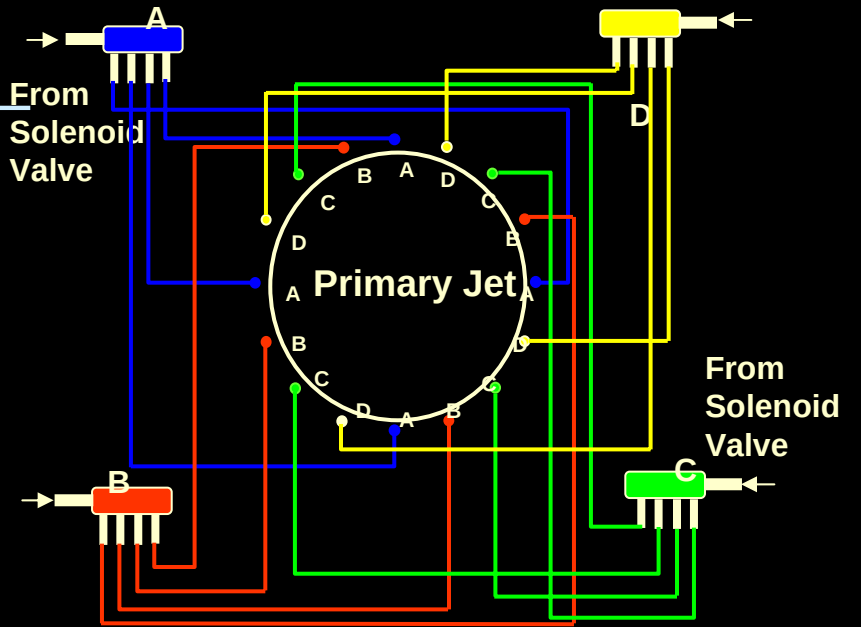
Experimental Details





M_{design}=1.5, NPR=2.5, 3.7,5
h/d=2~9





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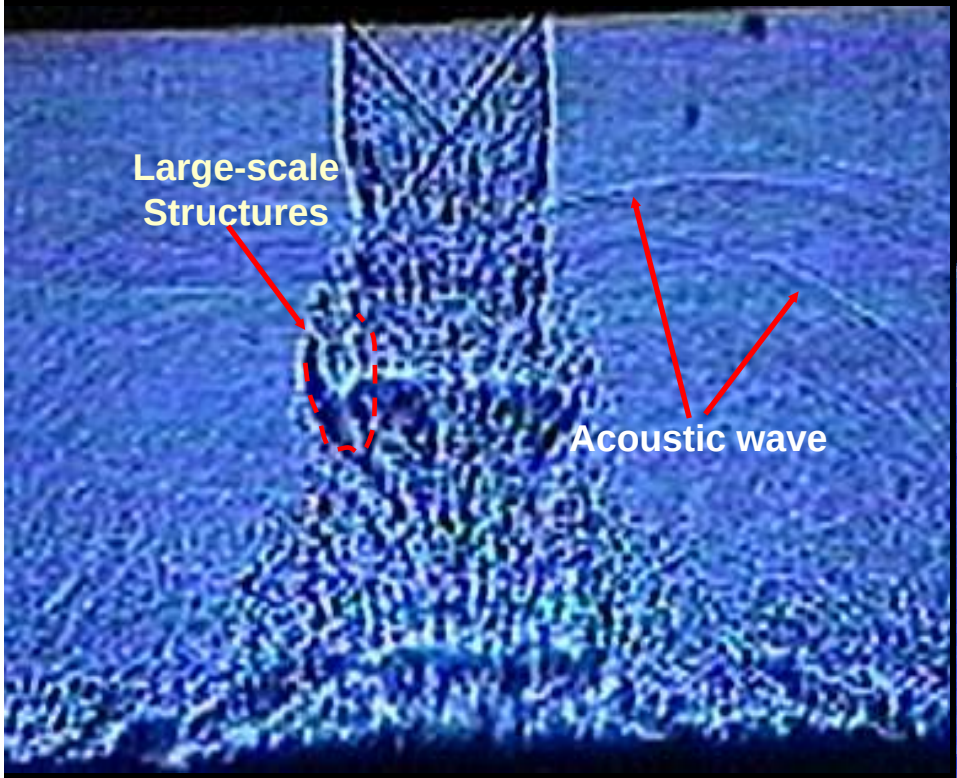
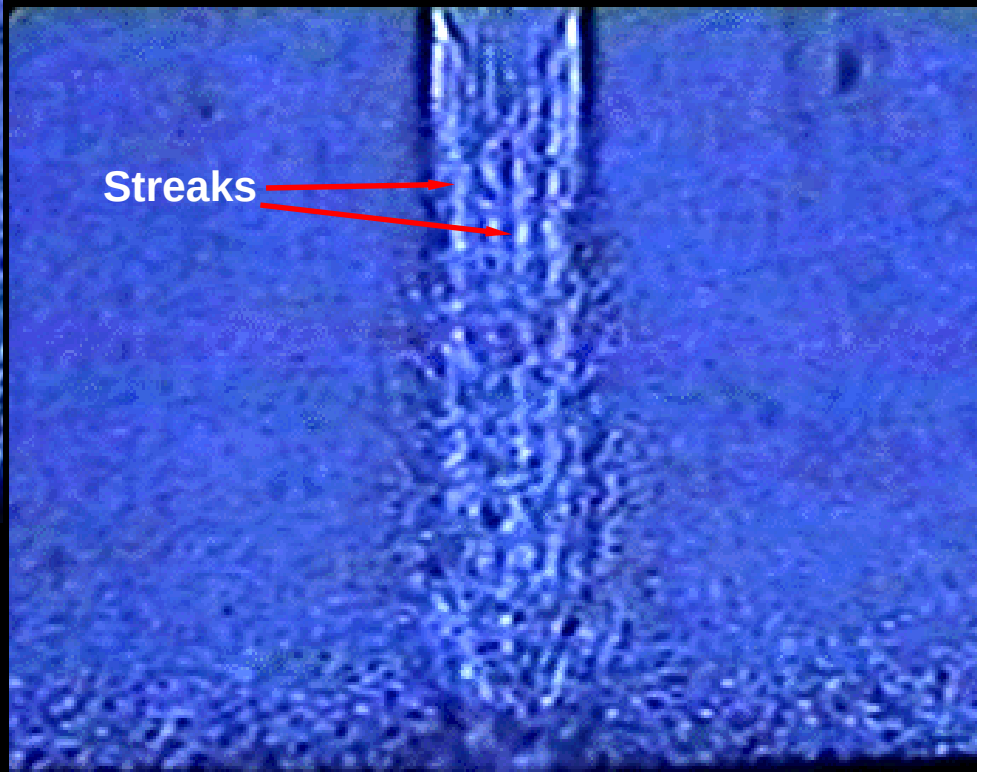
Effect of Microjet Control

Shadowgraphs NPR = 3.7, h/d = 4



No Control

With Control



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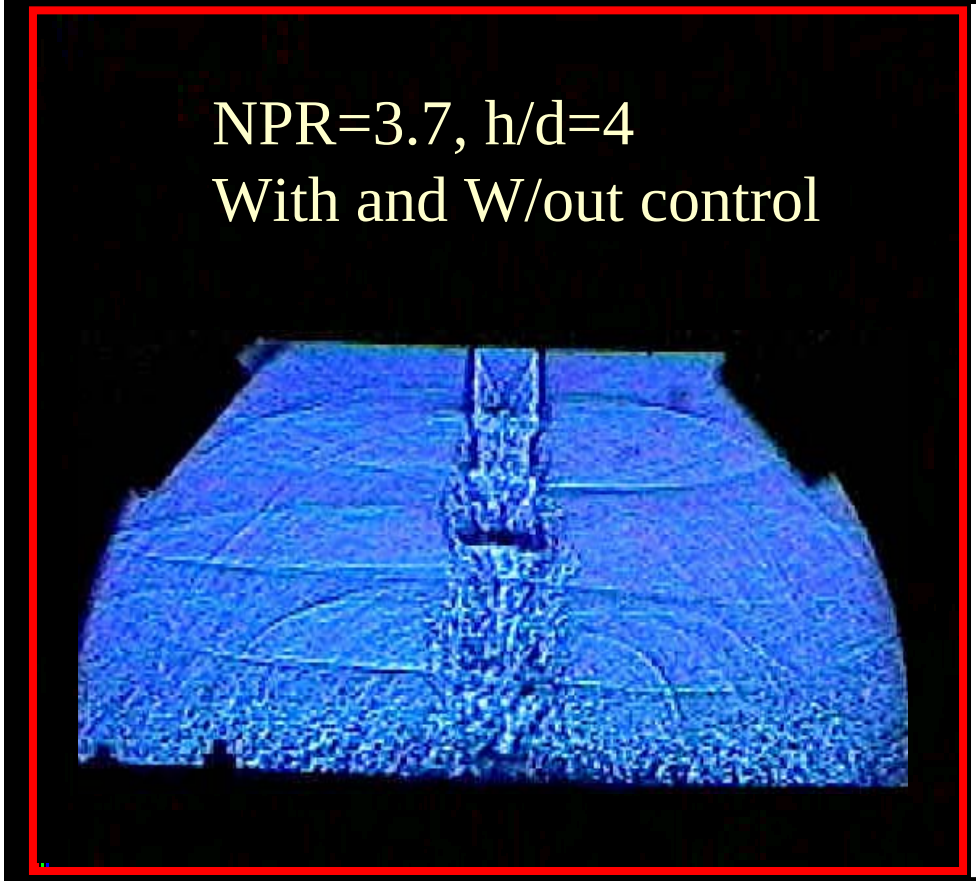
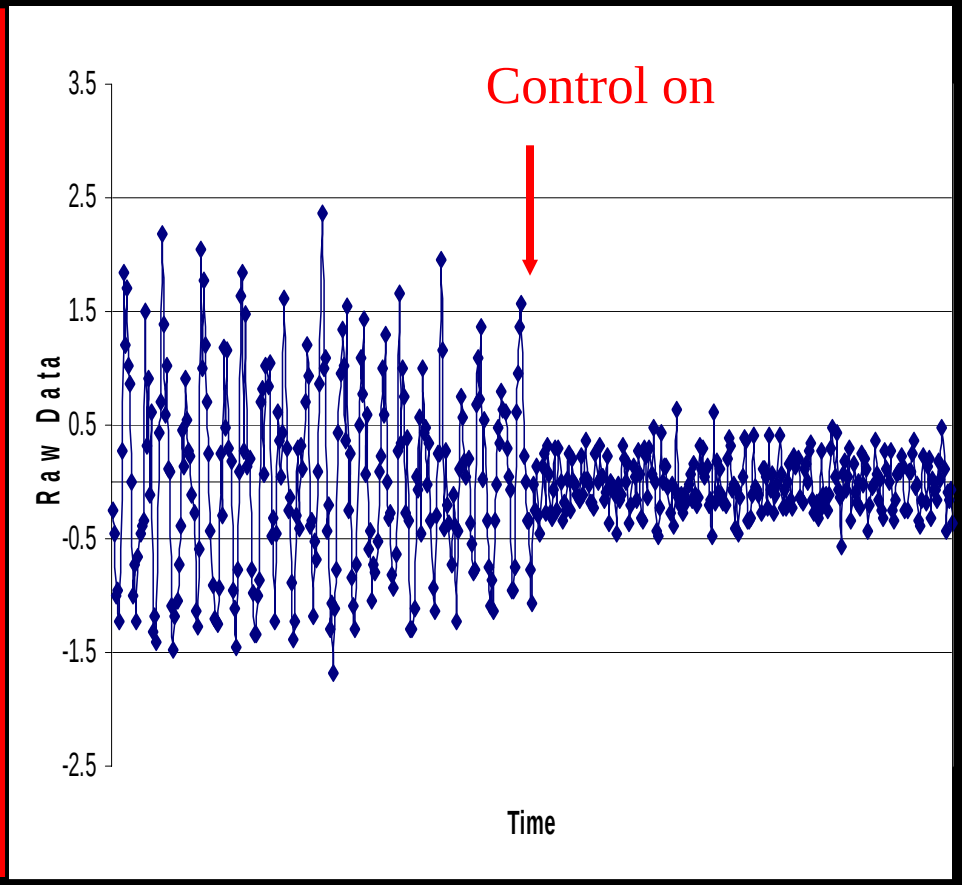
Effect of Microjet Control

NPR 3.7, h/D = 4





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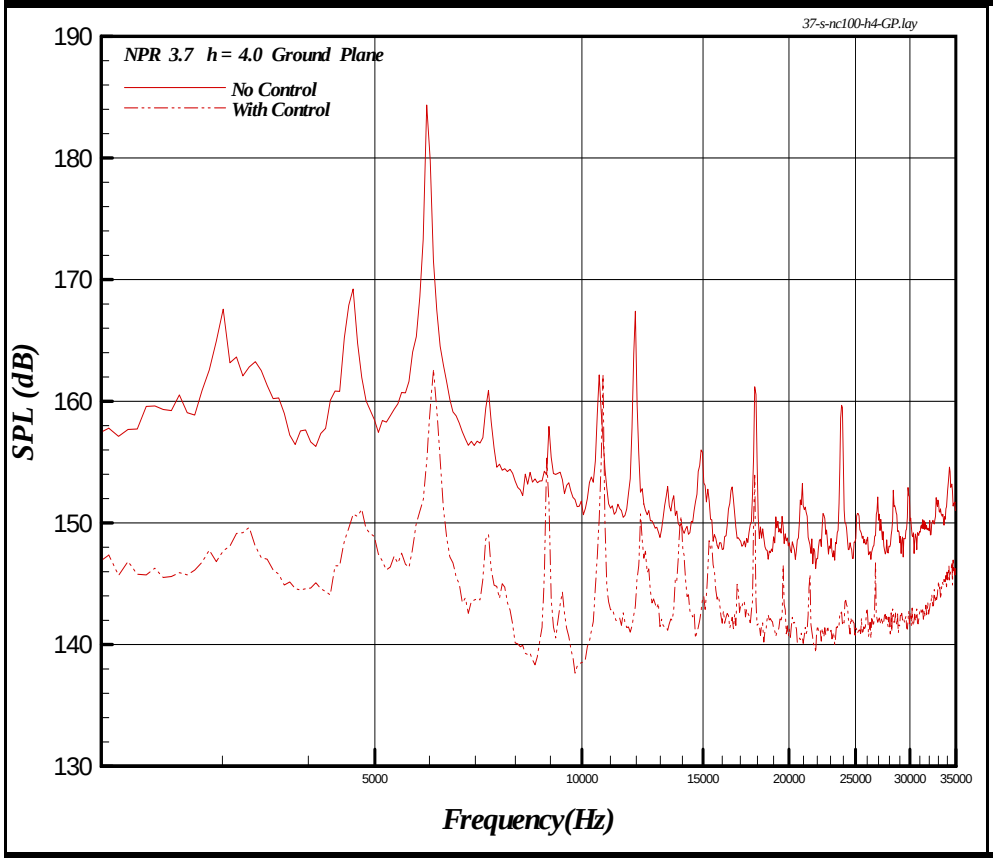
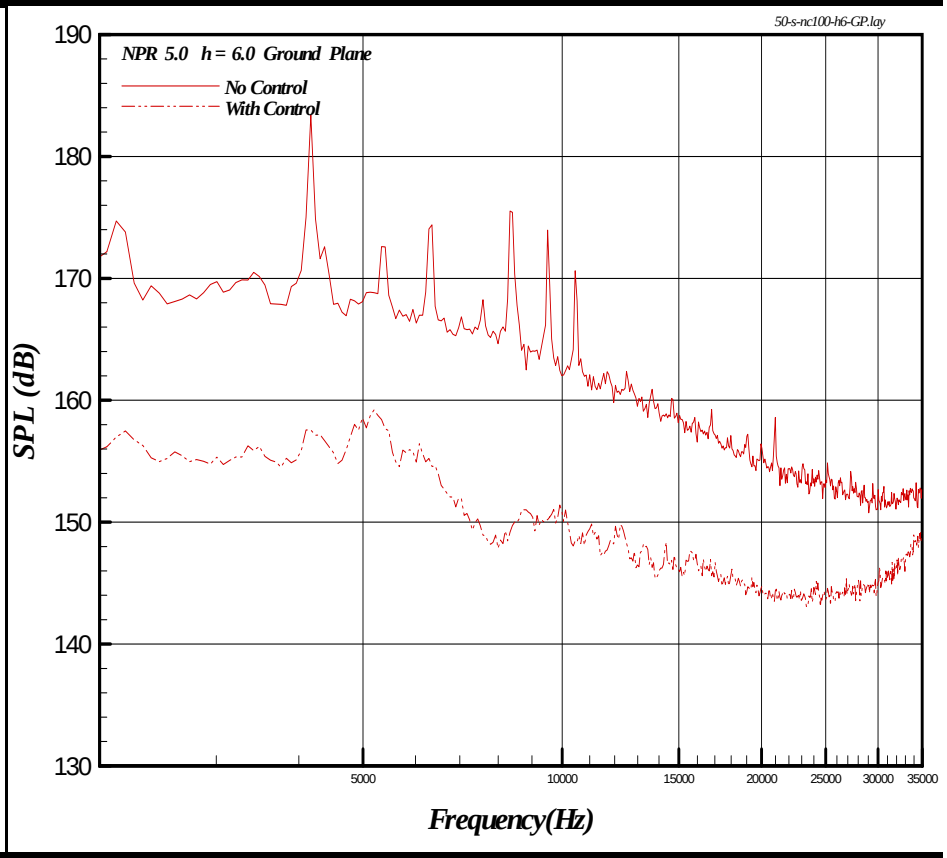
Pressure Spectra

Ground Plane





NPR 3.7

No Control
With Control

NPR 5

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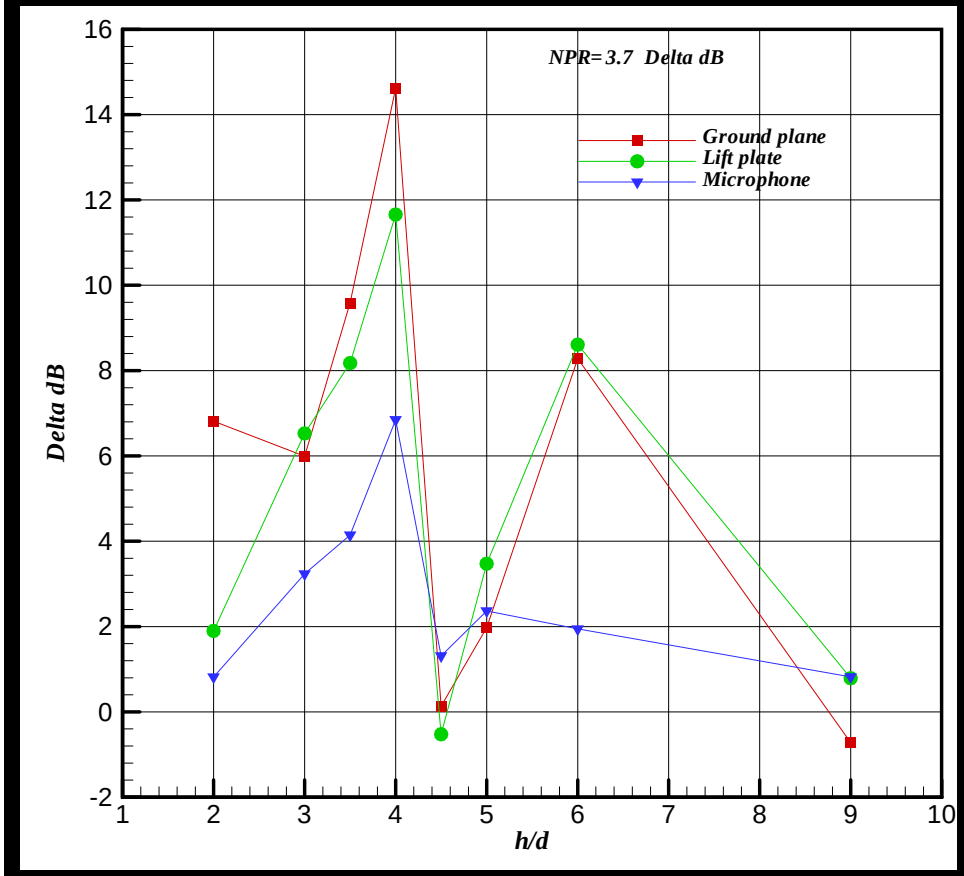
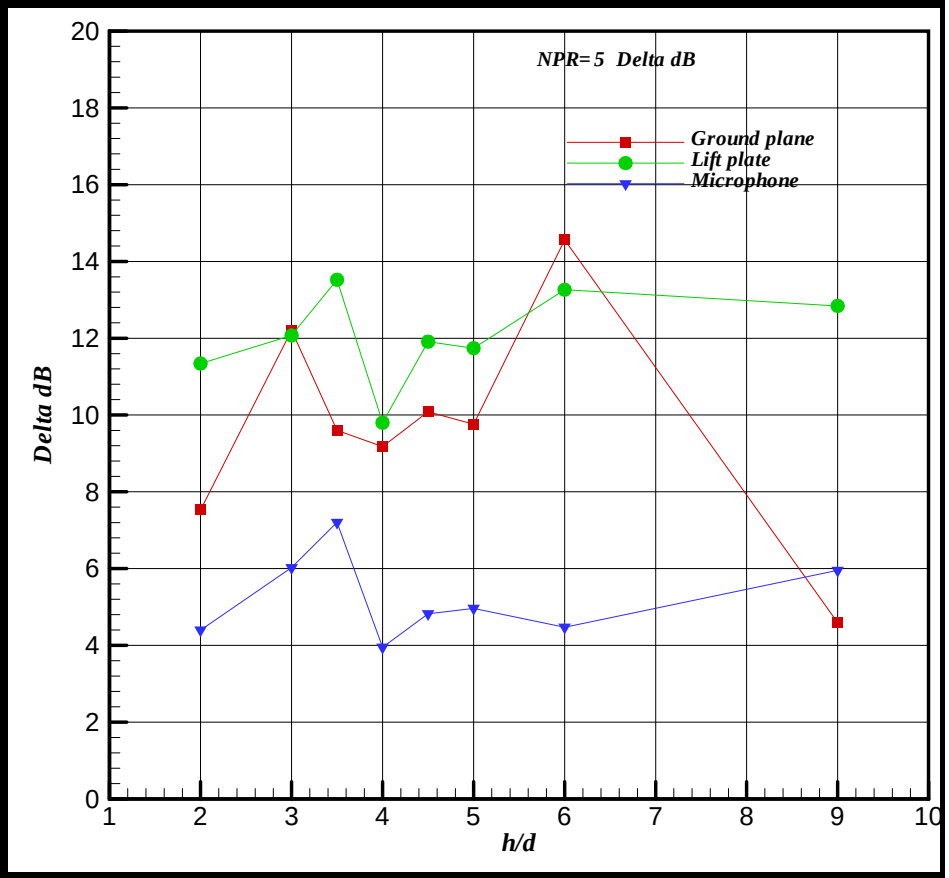
P_{rms} Reduction as a Function of Heights

20°, 100 psi, 16 microjets





NPR 3.7

Ground Plane
Lift Plate
Microphone

NPR 5.0

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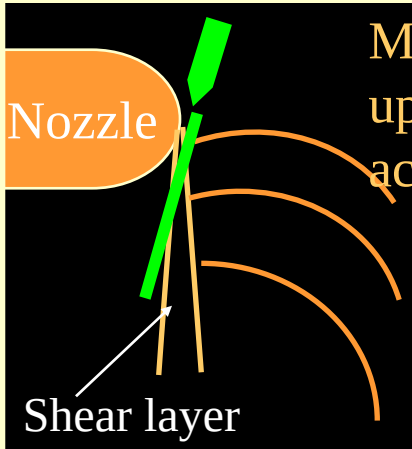
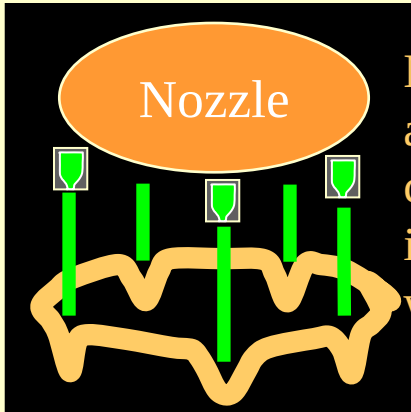
Why do the microjets work?

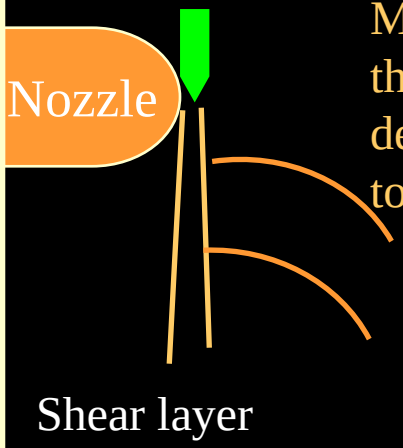


Microjet **intercept** upstream-propagating acoustic disturbances

Acoustic wave



Microjets disrupt the axisymmetric coherent coupling between instability & acoustic waves



Microjets **thicken** the nozzle shear layer, decreasing its receptivity to acoustic disturbances

Acoustic wave

Microjets introduce significant streamwise vorticity, thus weak the large-scale structures

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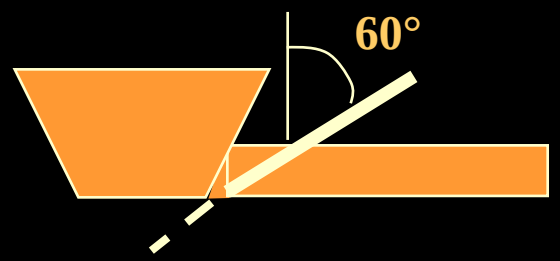
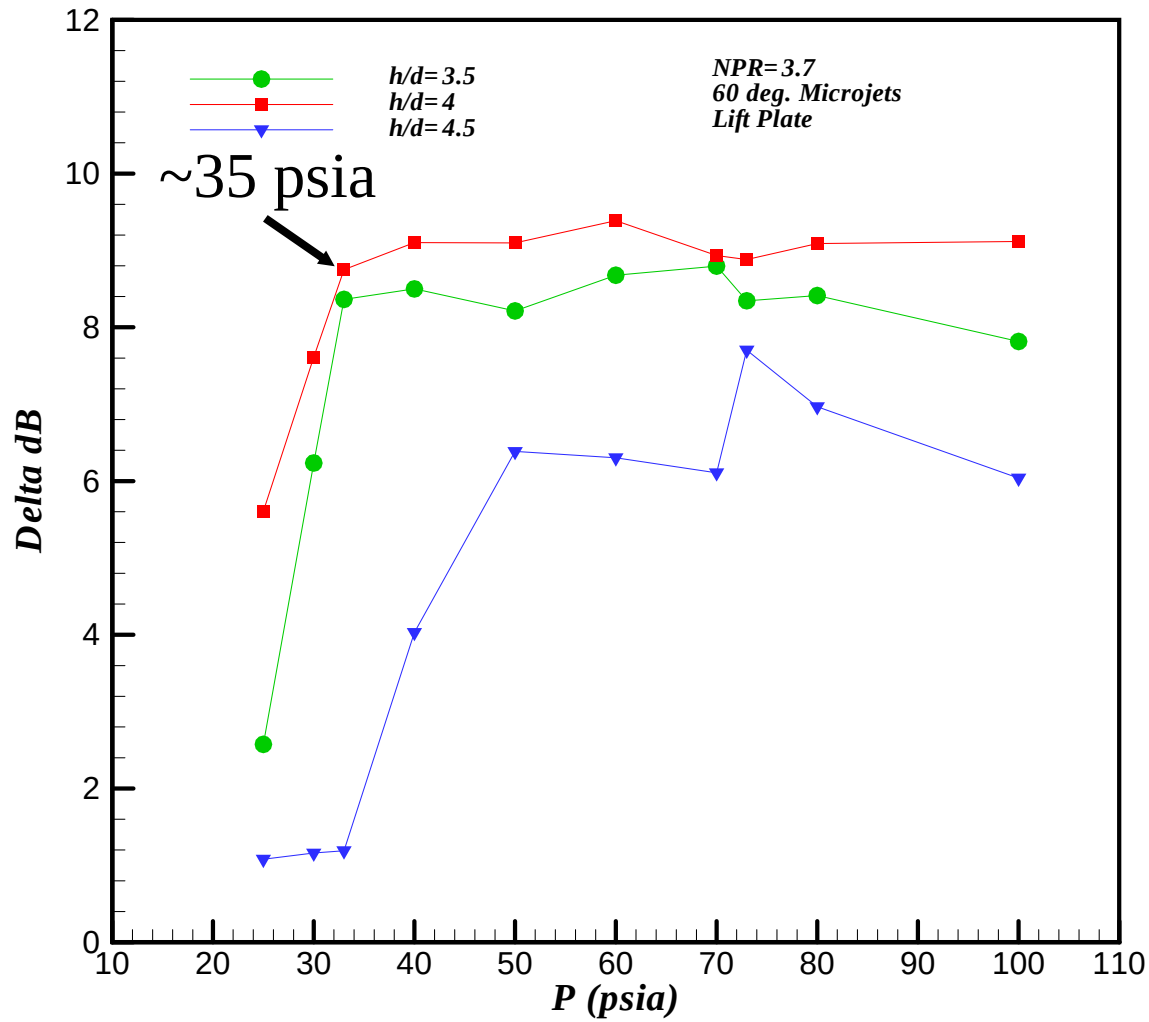
Effect of Microjet Pressure

NPR=3.7, 60 deg. microjet



$$\dot{M} = \gamma M_e^2 \frac{\rho_e}{\rho_0} \frac{a_e^2}{a_0^2} P_0$$

h/d=3.5
h/d=4
h/d=4.5



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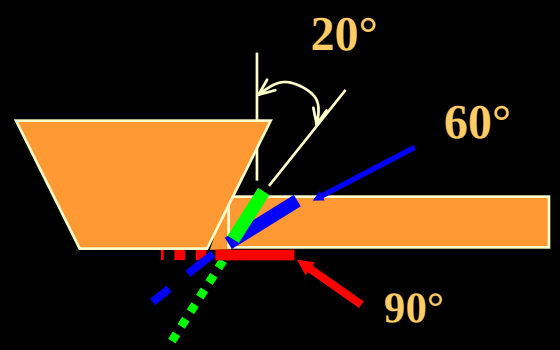
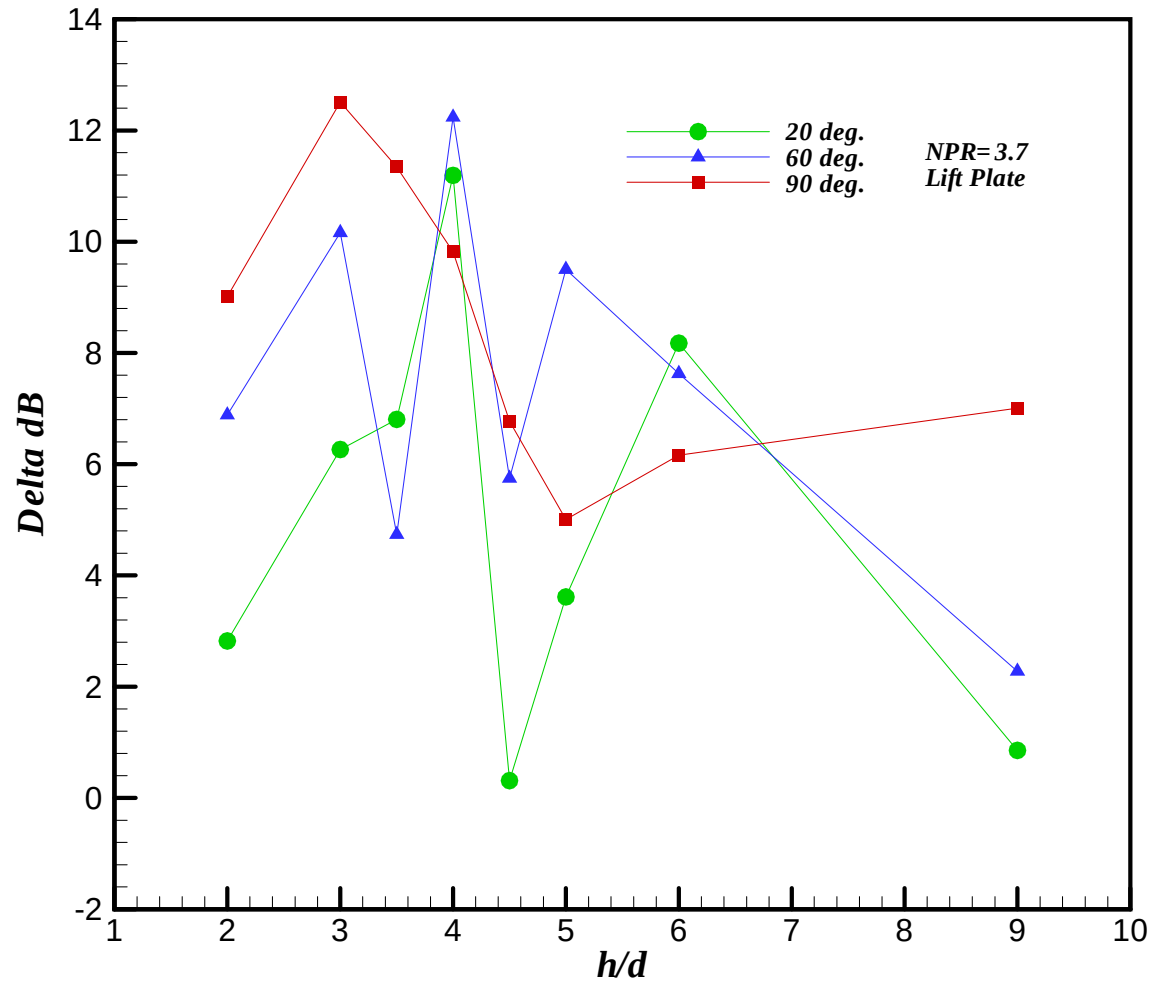
Effect of Microjet Angle

Microjet pressure @ 100psia



20 deg. microjets
60 deg. microjets
90 deg. microjets



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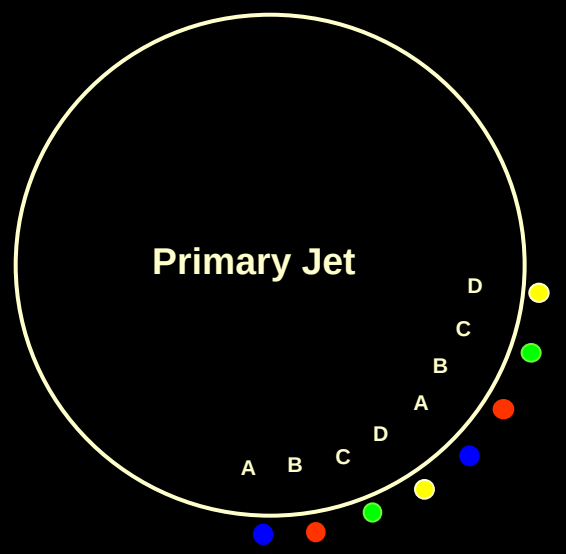
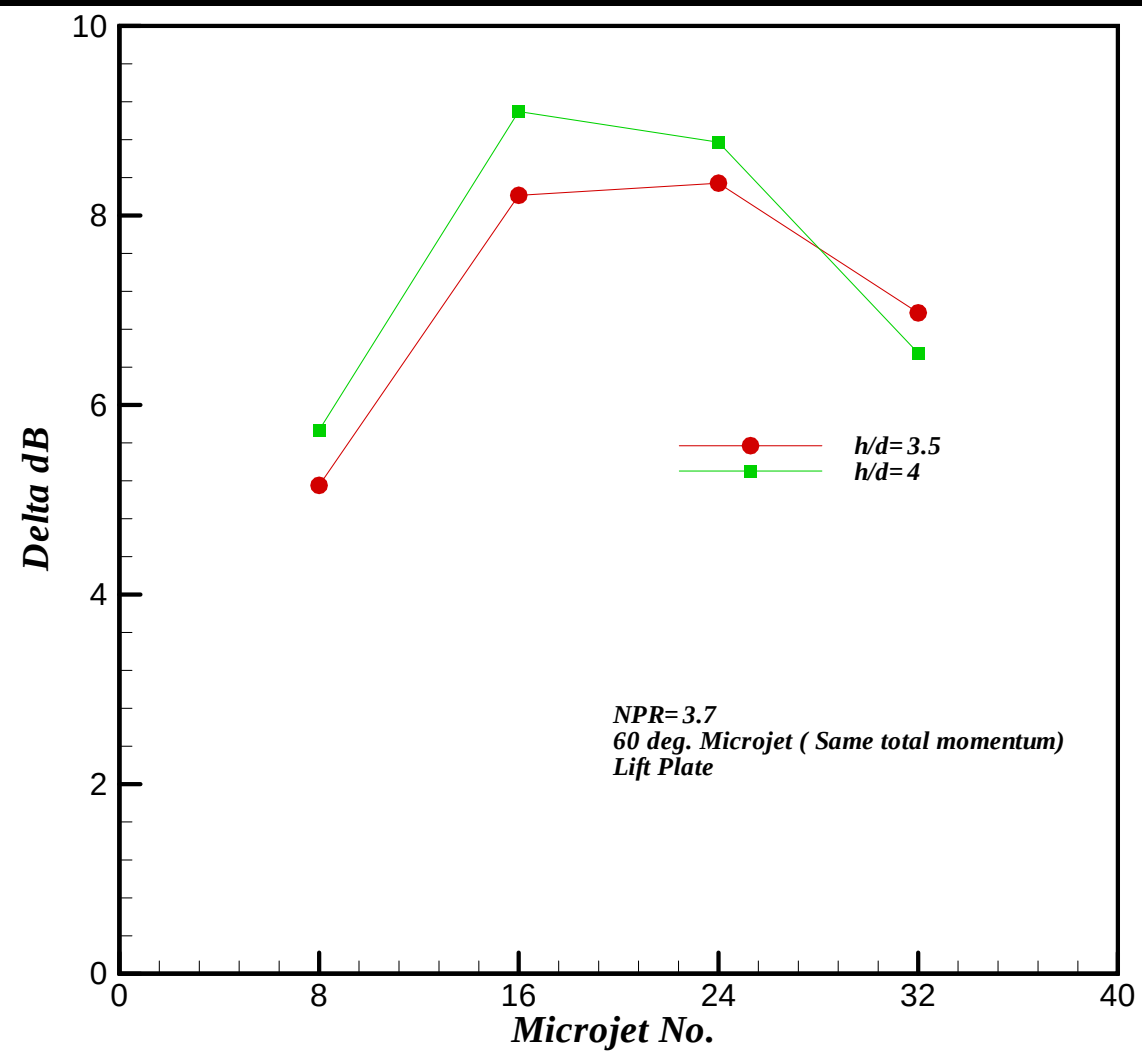
Effect of Microjet Spacing

NPR=3.7, 60 deg. Microjet @ fixed total momentum



8 microjets: Bank A
16 microjets: Bank A, C
32 microjets: Bank A, B, C
32 microjets: Bank A, B, C, D



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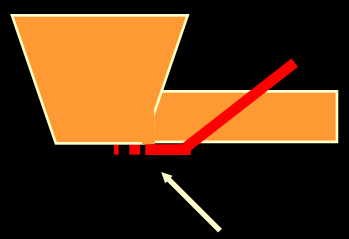
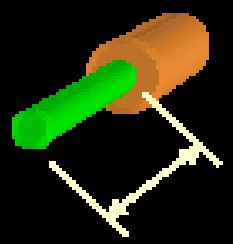
Effect of Micro-tabs

NPR=3.7



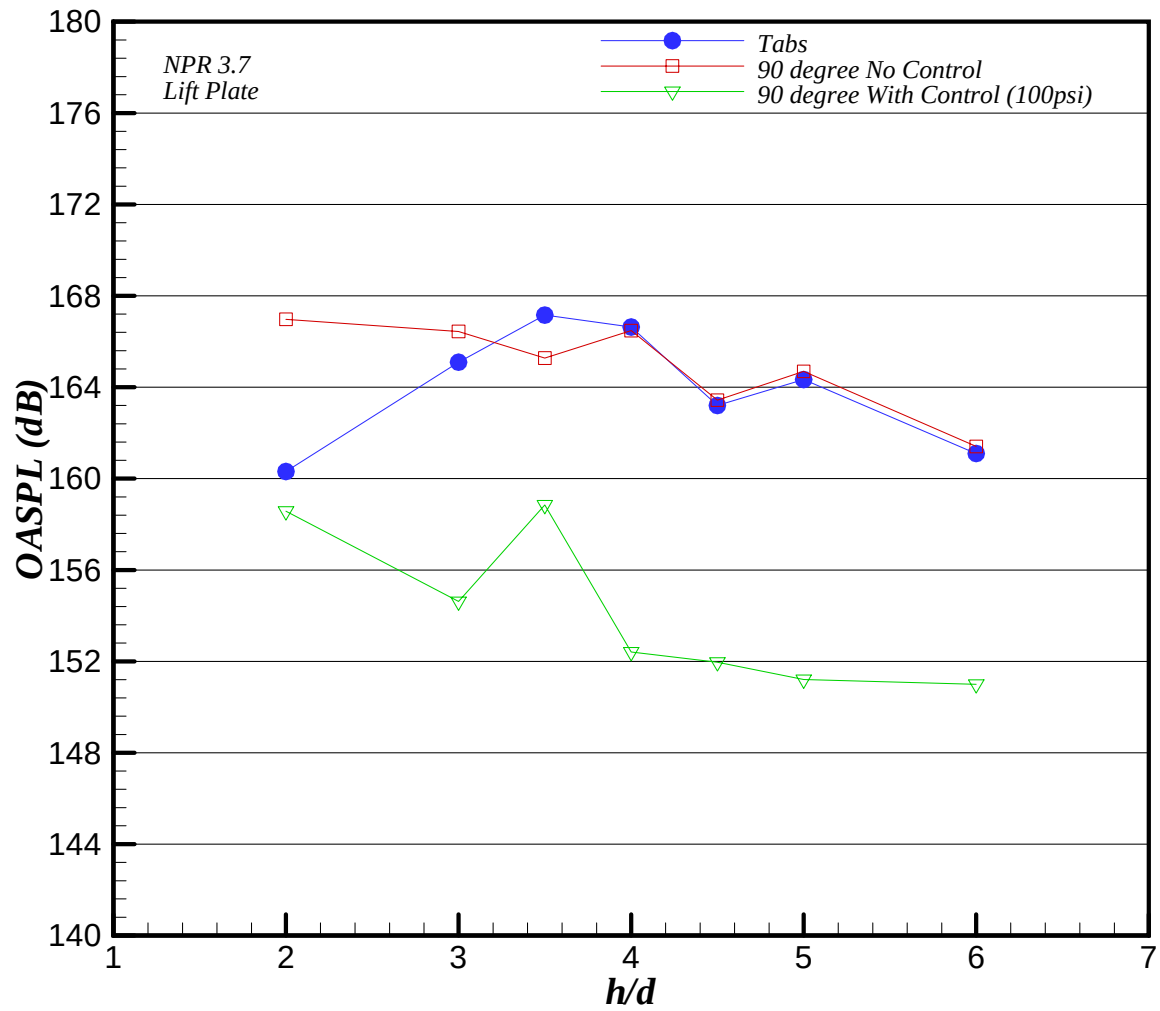
90° Microjets

Micro-tabs



400 µm dia.
2.5 mm length

Tab.
90 deg. No Control
90 deg. With Control



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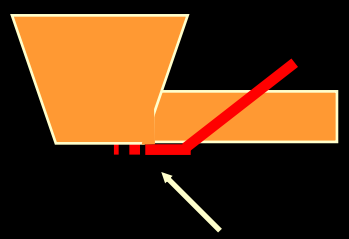
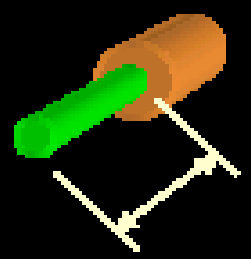
Effect of Micro-tabs

NPR=5



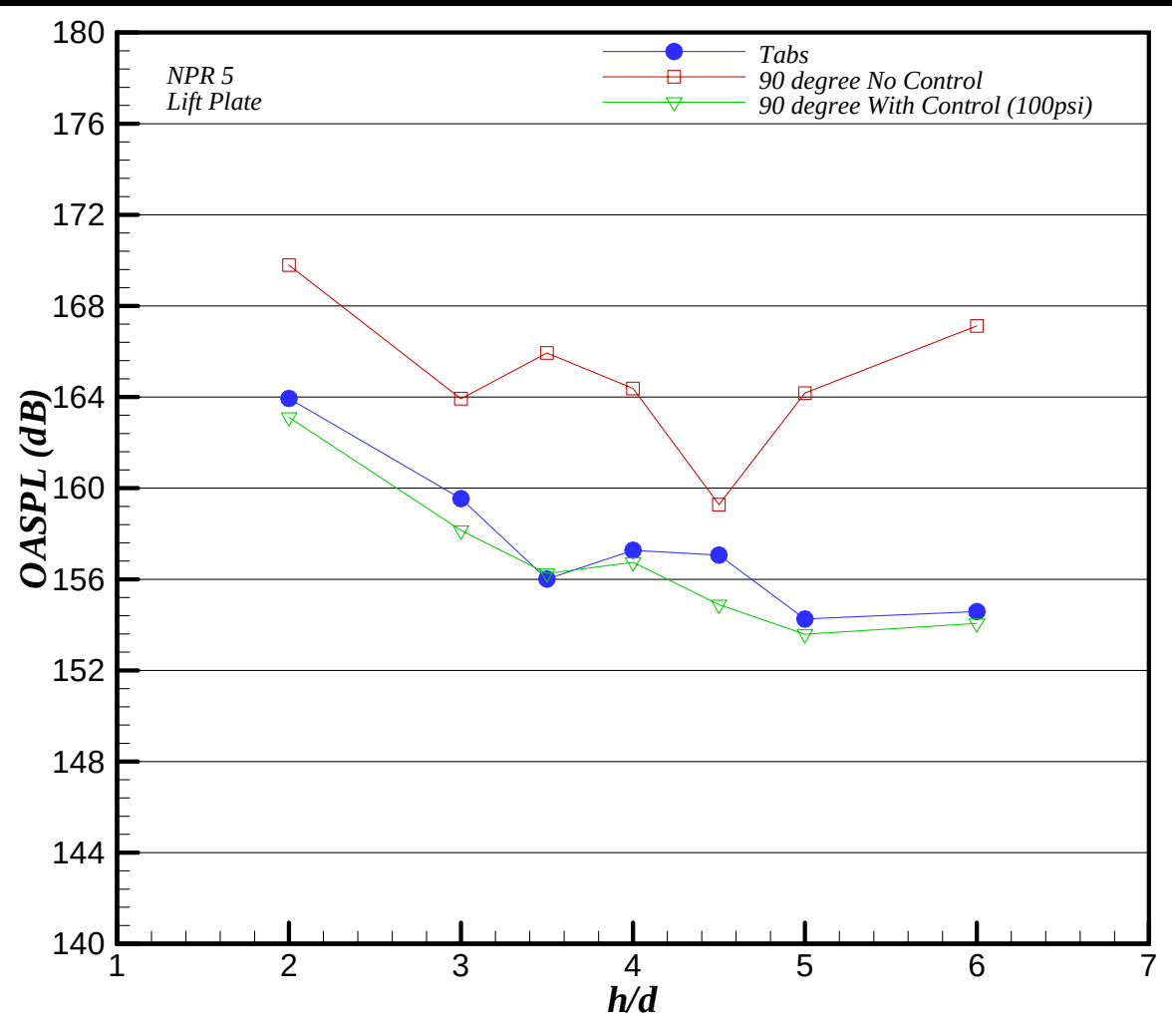
90° Microjets

Micro-tabs



400 µm dia.
2.5 mm length

Tab.
90 deg. No Control
90 deg. With Control



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Summary of Parametric Effects

- **Microjet control suppresses the flow unsteadiness and reduces the noise level:**
  - **Impinging tones are completely eliminated or significantly reduced**
  - **Overall noise/dynamic pressures are reduced by 5-12 dB**
- **The substantial improvement on the reduction was achieved when the microjet angle changed from 20° to 60° or 90°**
- **The effectiveness of microjet control strongly depend on the microjet pressure for NPR=3.7, but less sensitive for NPR=5**
- **The effectiveness of microjet control also depend on microjet spacing**
- **Micro-tabs show no effect at NPR=3.7, but have almost same effect as microjet control for NPR=5.**

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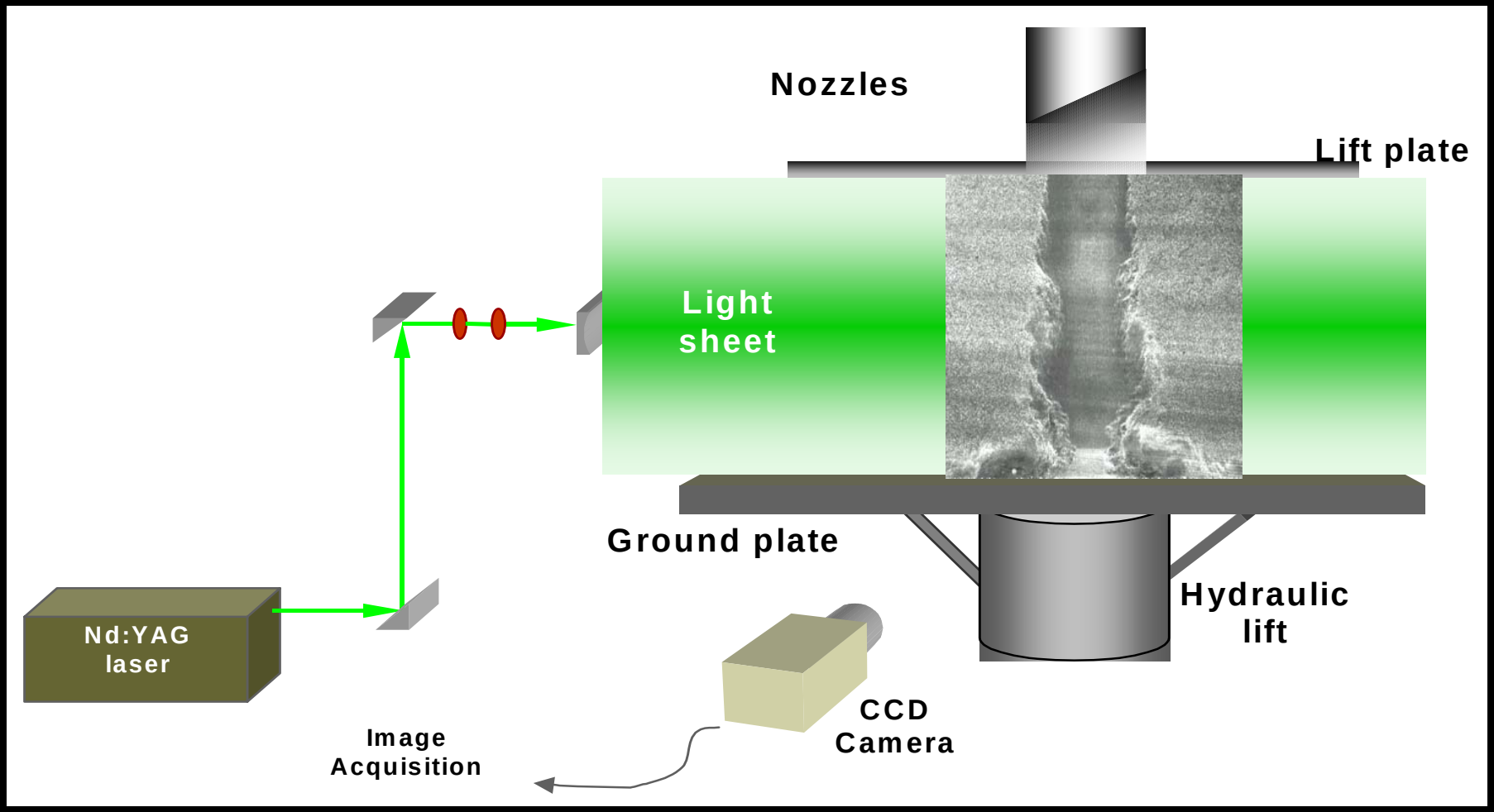
Experiment Setup



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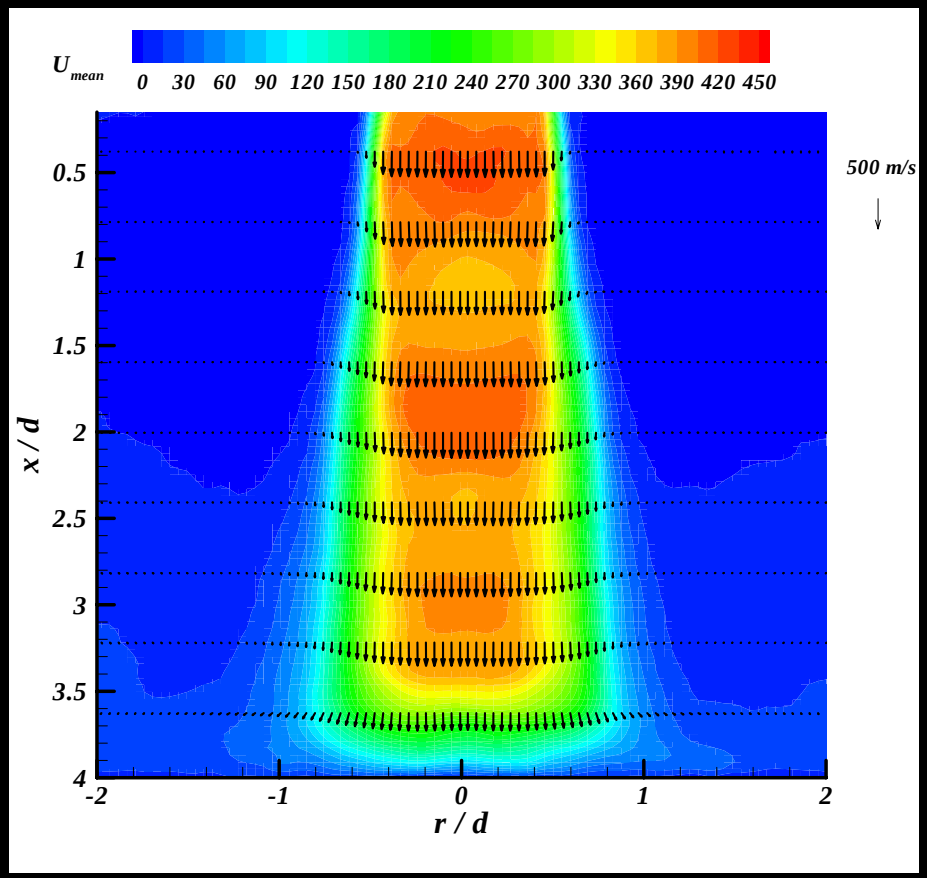
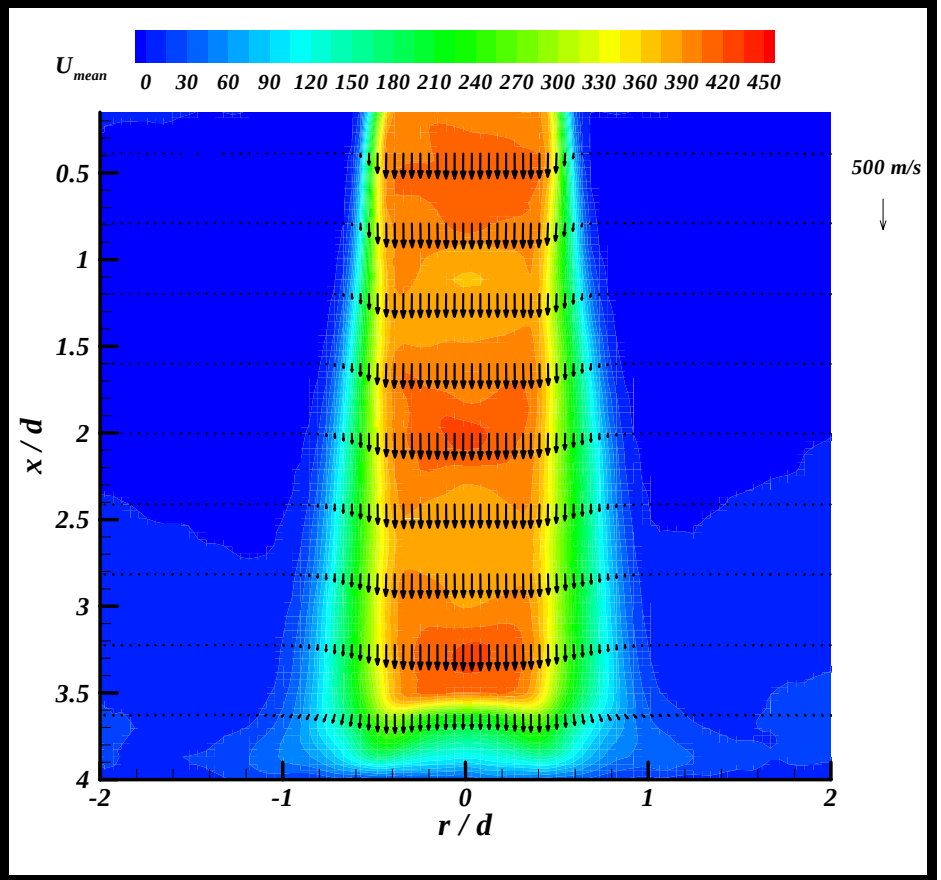
Effect of Microjet Control on Mean Velocity

NPR=3.7, h/d=4, 90 deg. μjet



No Control



With Control

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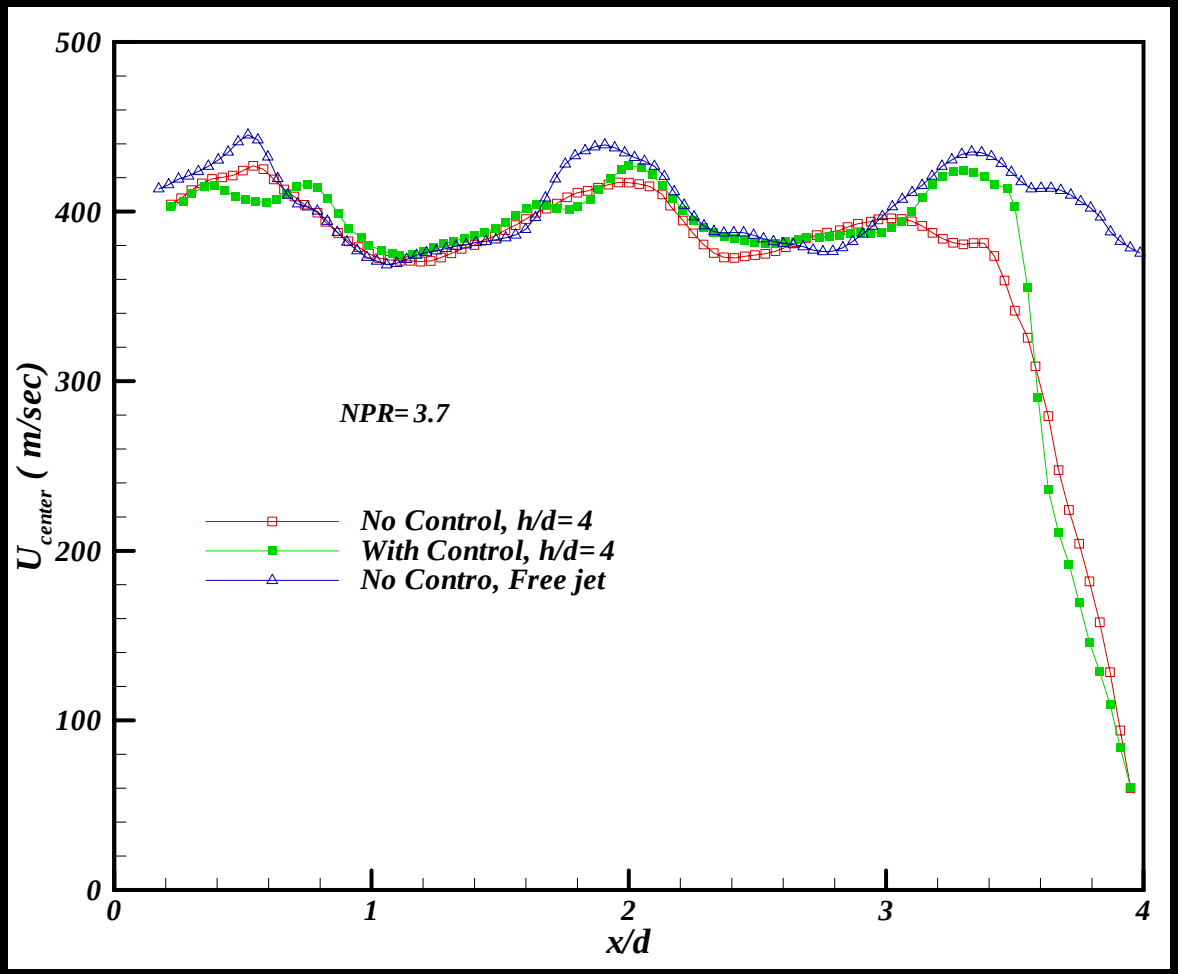
Effect of Microjet Control on Centerline Velocity

NPR=3.7, h/d=4, 90 deg. μjet



No Control
With Control
Free Jet

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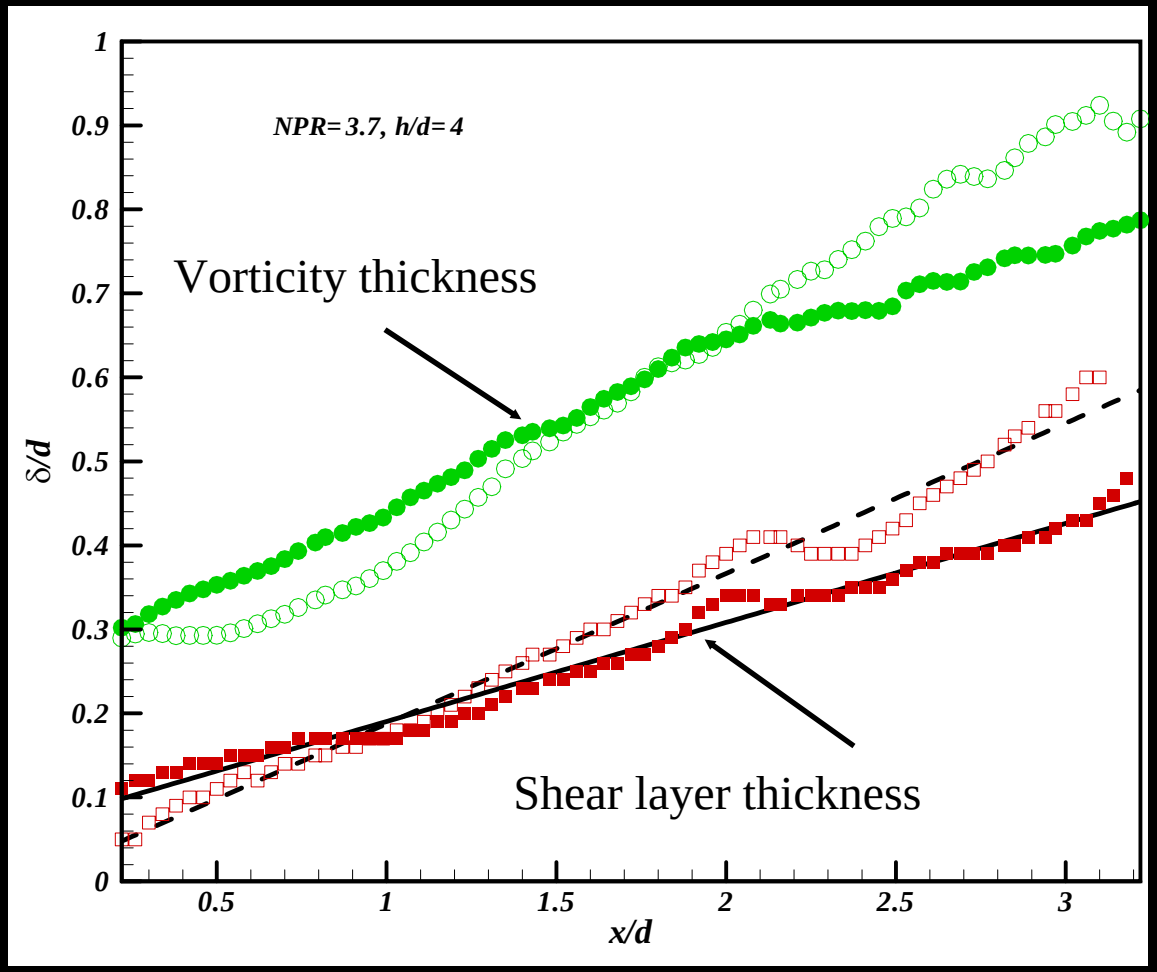
Effect of Microjet Control on Shear Layer Thickness

NPR=3.7, h/d=4, 90 deg. μjet



○, □, No Control
●, ■, With Control

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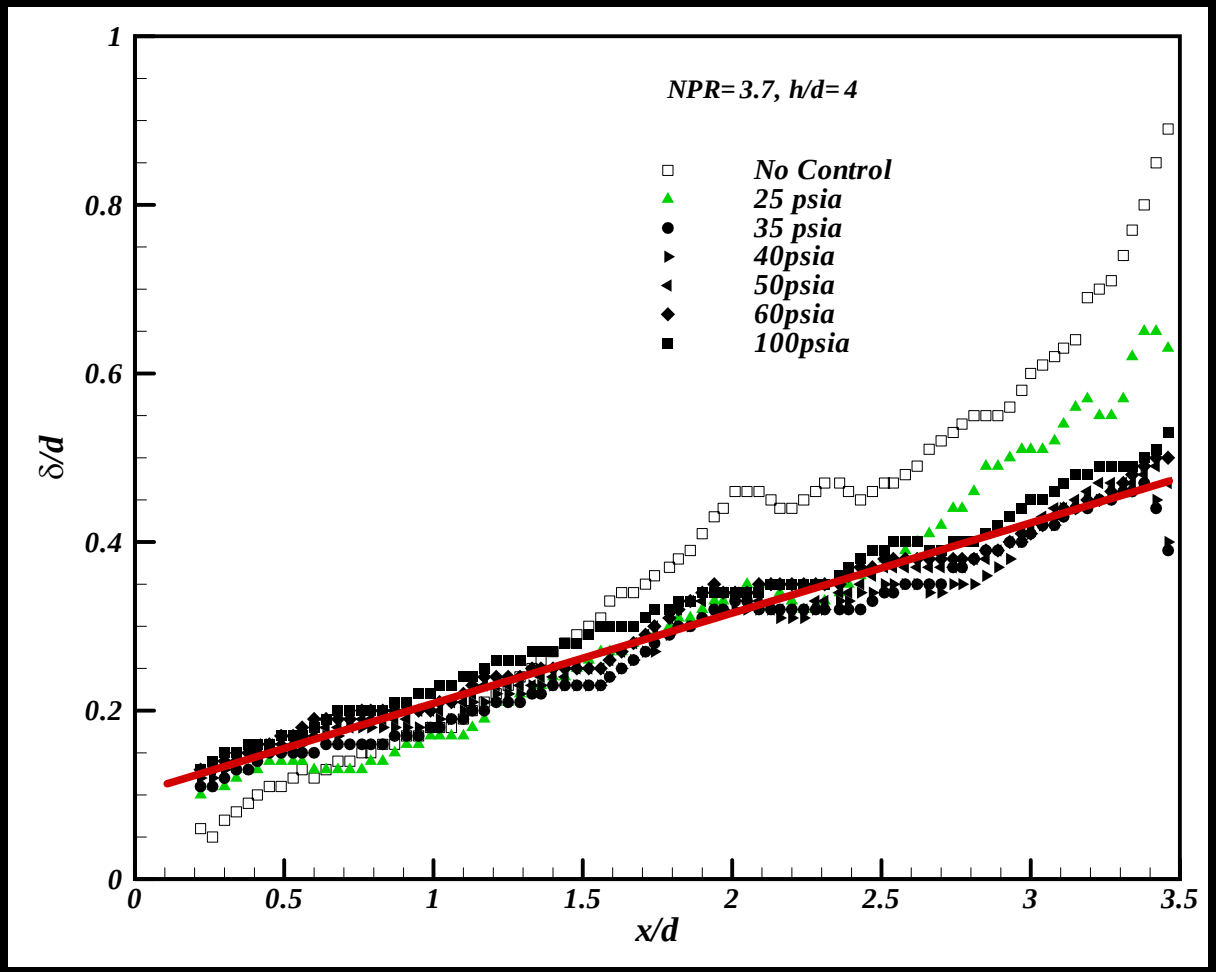
Effect of Microjet Pressure on Shear Layer Thickness

NPR=3.7, h/d=4, 60 deg. μjet

25 ~ 100 psia



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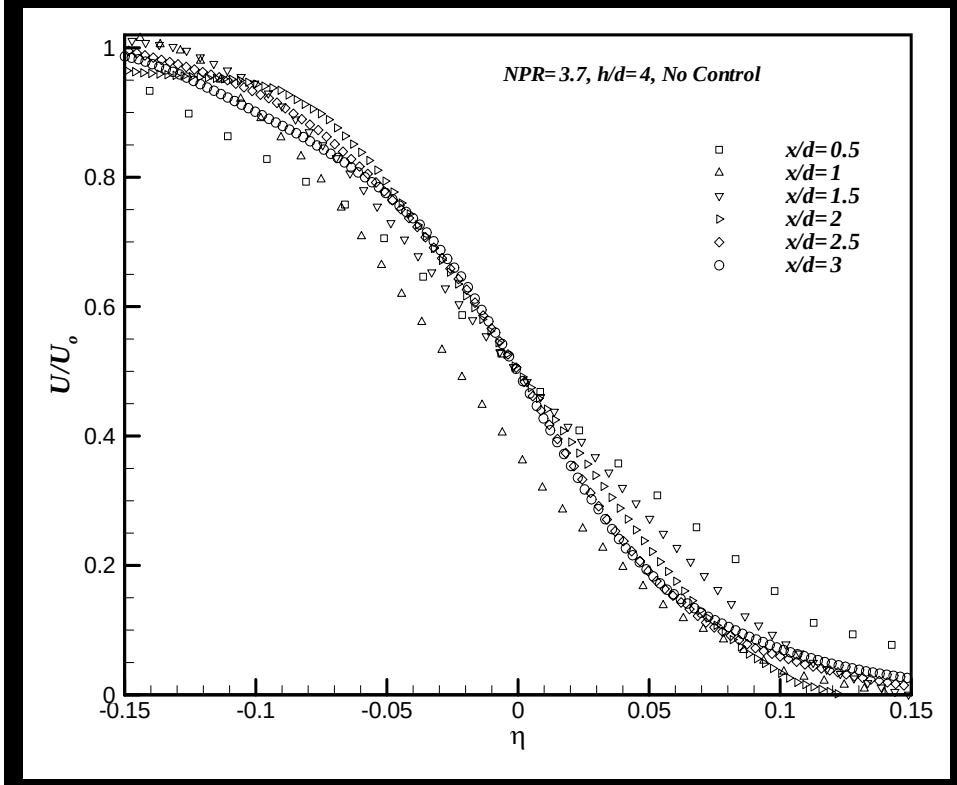
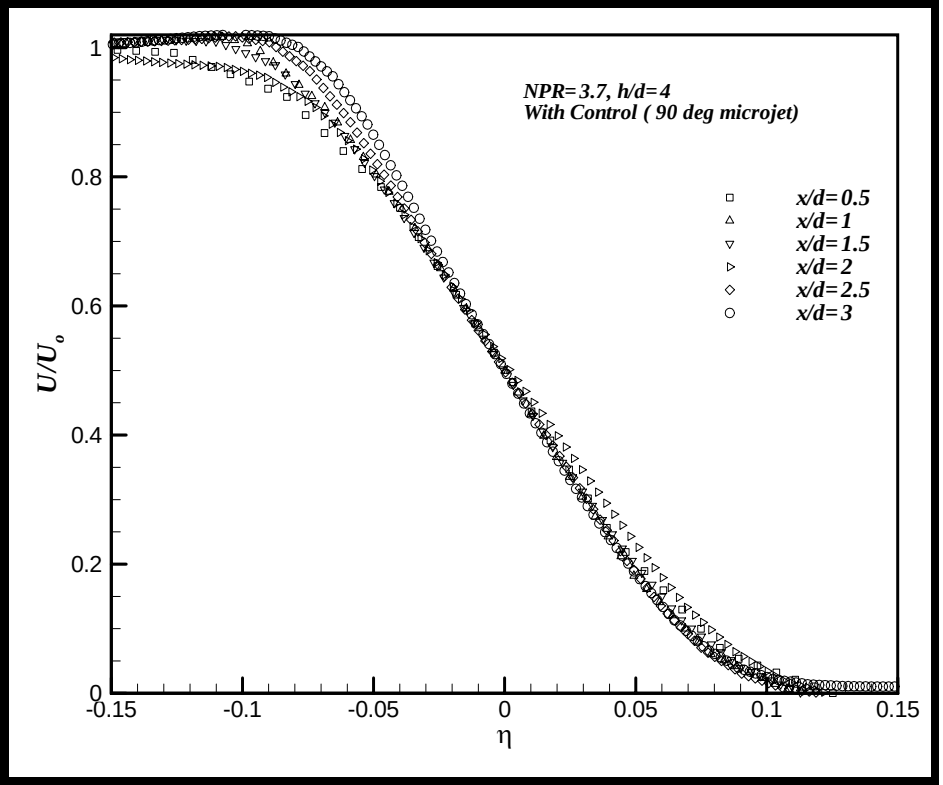
Effect of Microjet Control on Velocity Profile

NPR=3.7, h/d=4, 90 deg. μjet





No Control **With Control**

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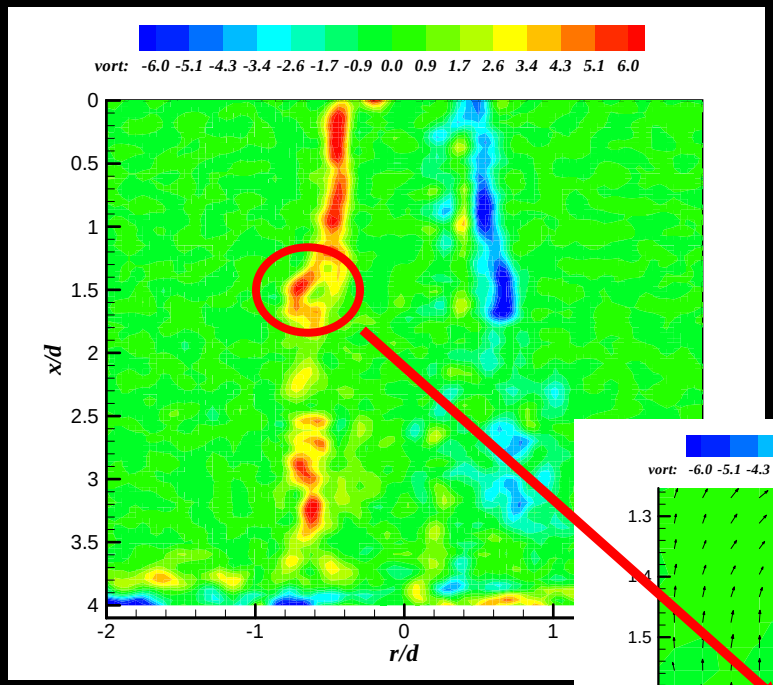
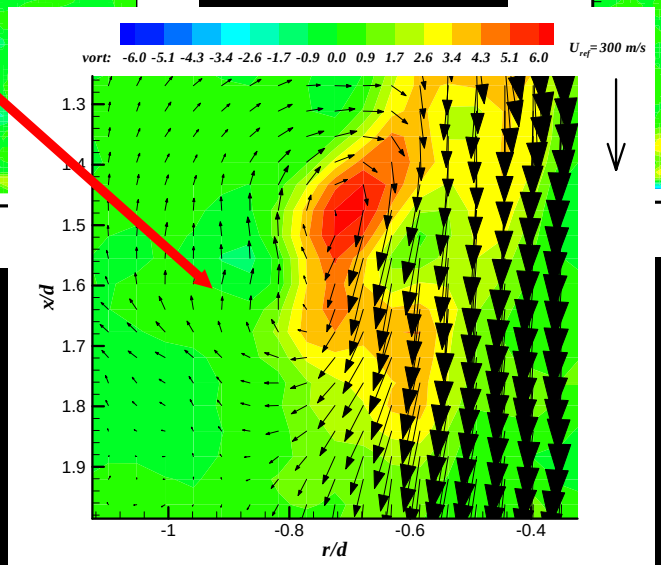
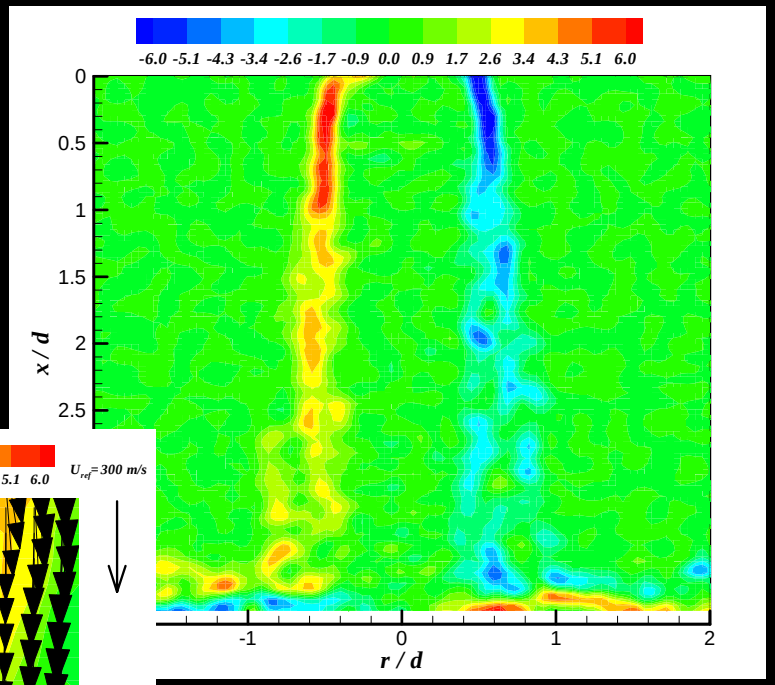
Instantaneous Vorticity Distribution

NPR=3.7, h/d=4, 90 deg. μjet







No Control

With Control

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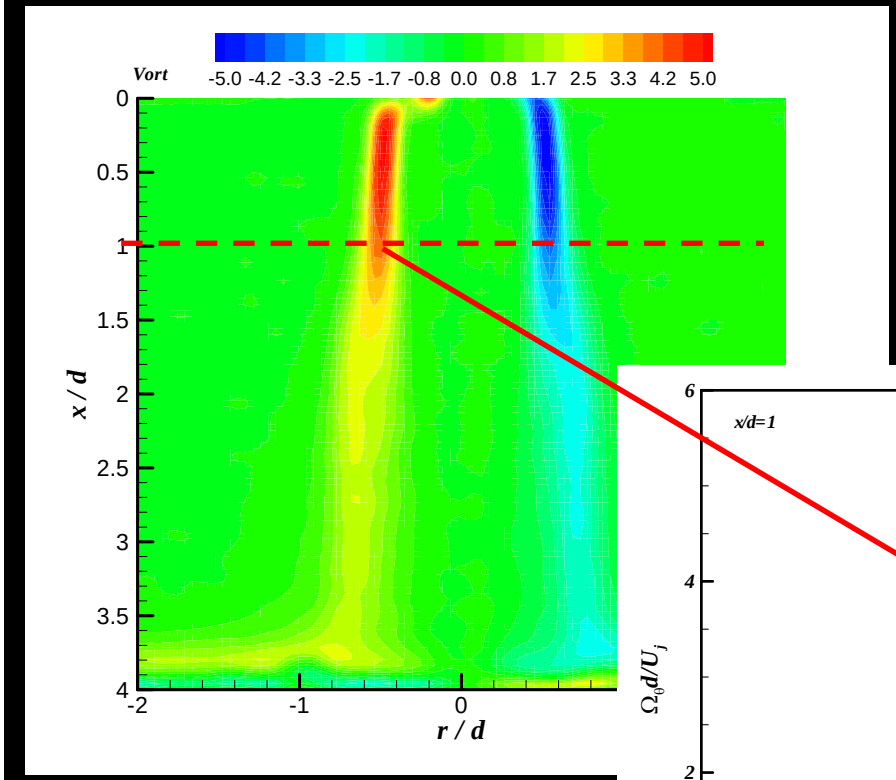
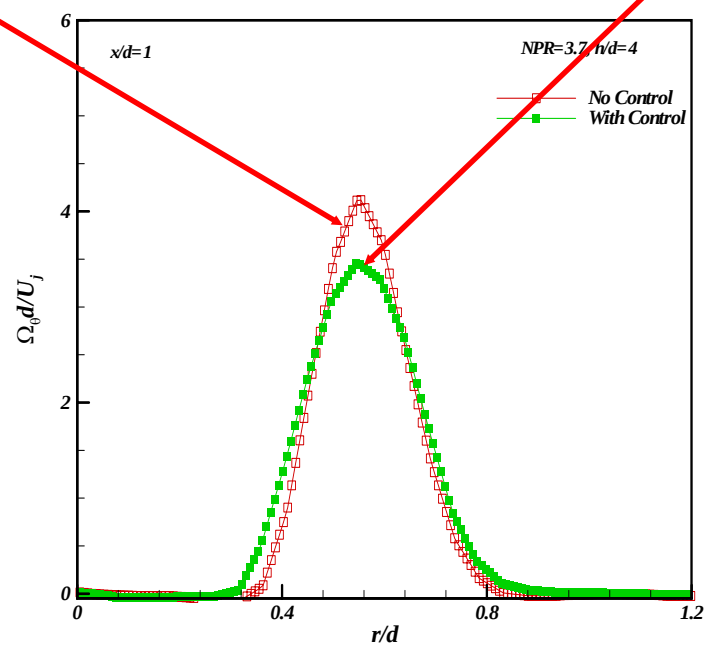
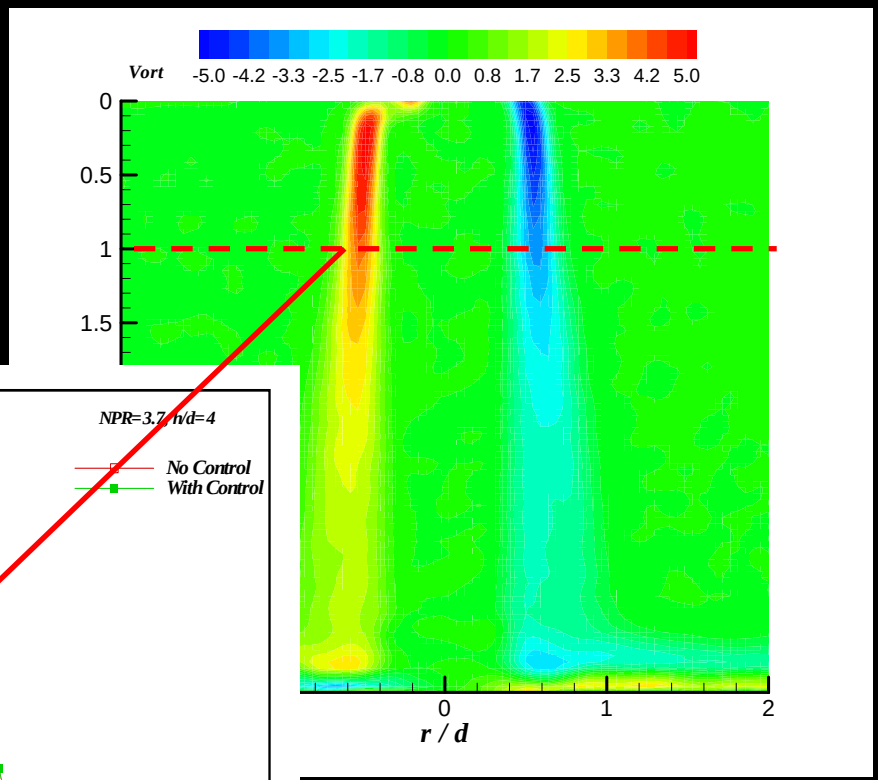
Effect of Microjet Control on Azimuthal Vorticity

NPR=3.7, h/d=4, 90 deg. μjet







No Control

With Control

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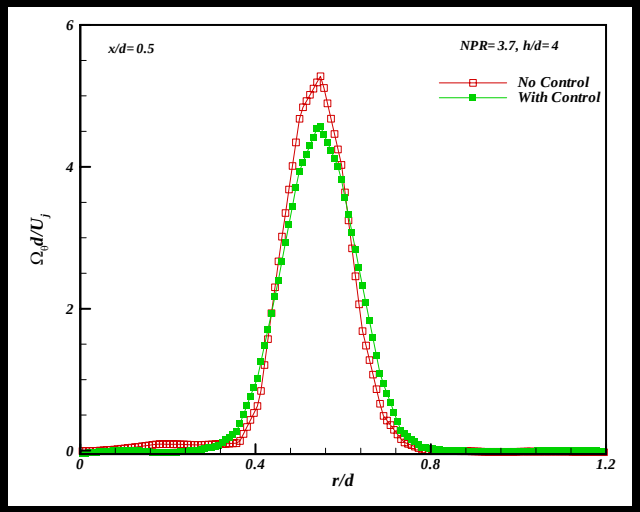
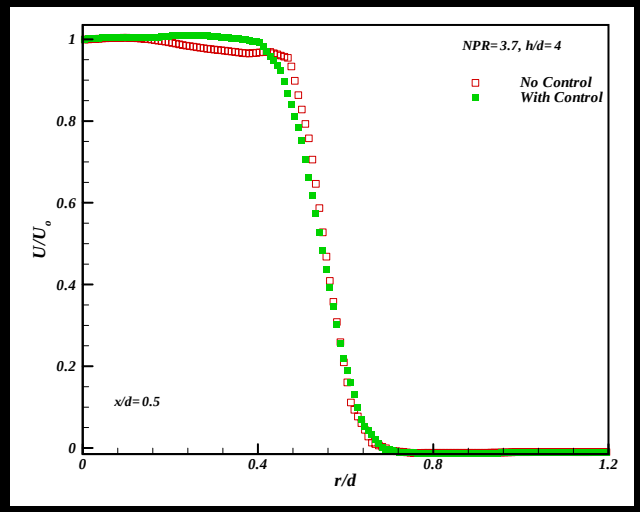
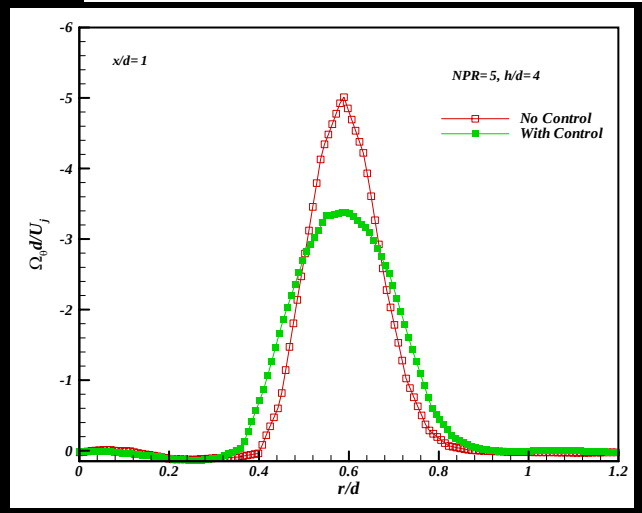
Effect of Microjet Control on Azimuthal Vorticity

h/d=4, 90 deg. μjet

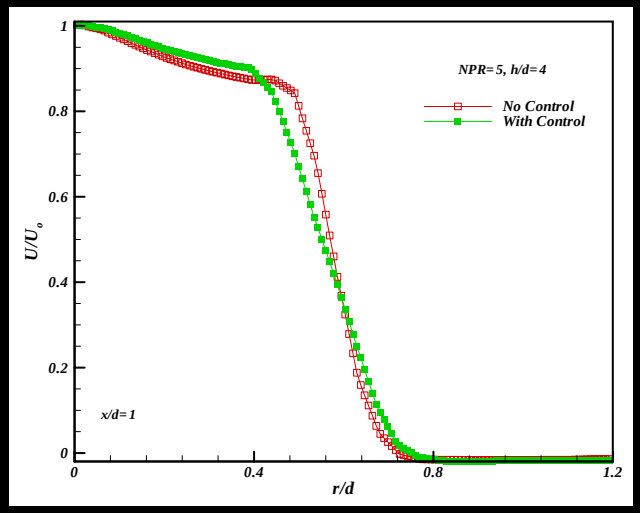




NPR=3.7



Vorticity



Velocity

No Control
With Control

NPR=5

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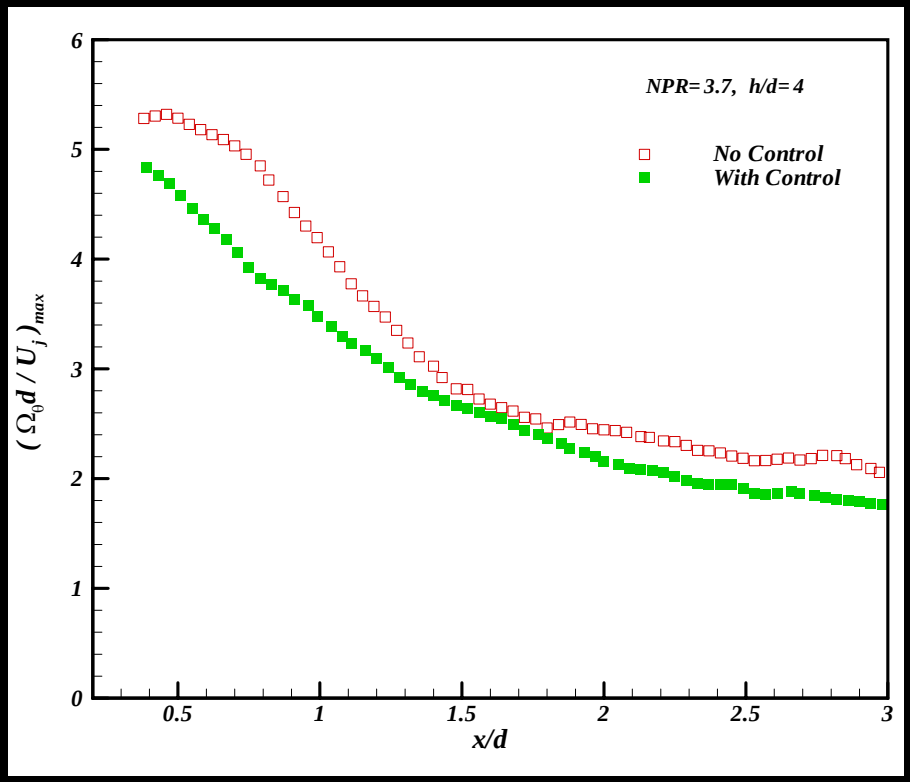
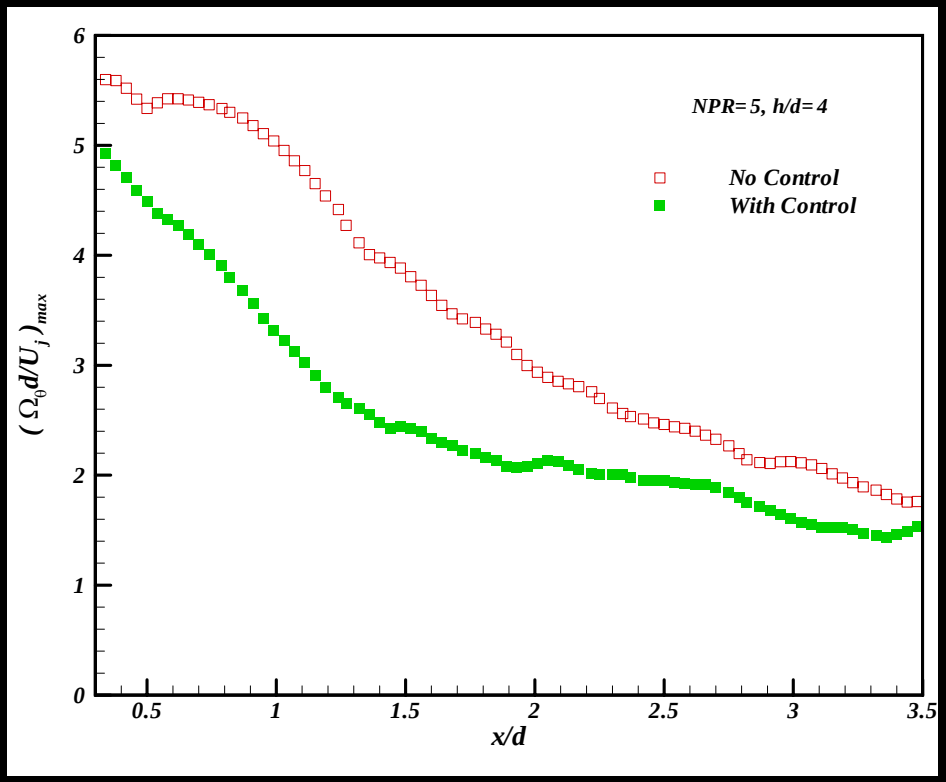
Effect of Microjet Control on Peak Azimuthal Vorticity

No Control
With Control

h/d=4, 90 deg. μjet



NPR=3.7



NPR=5

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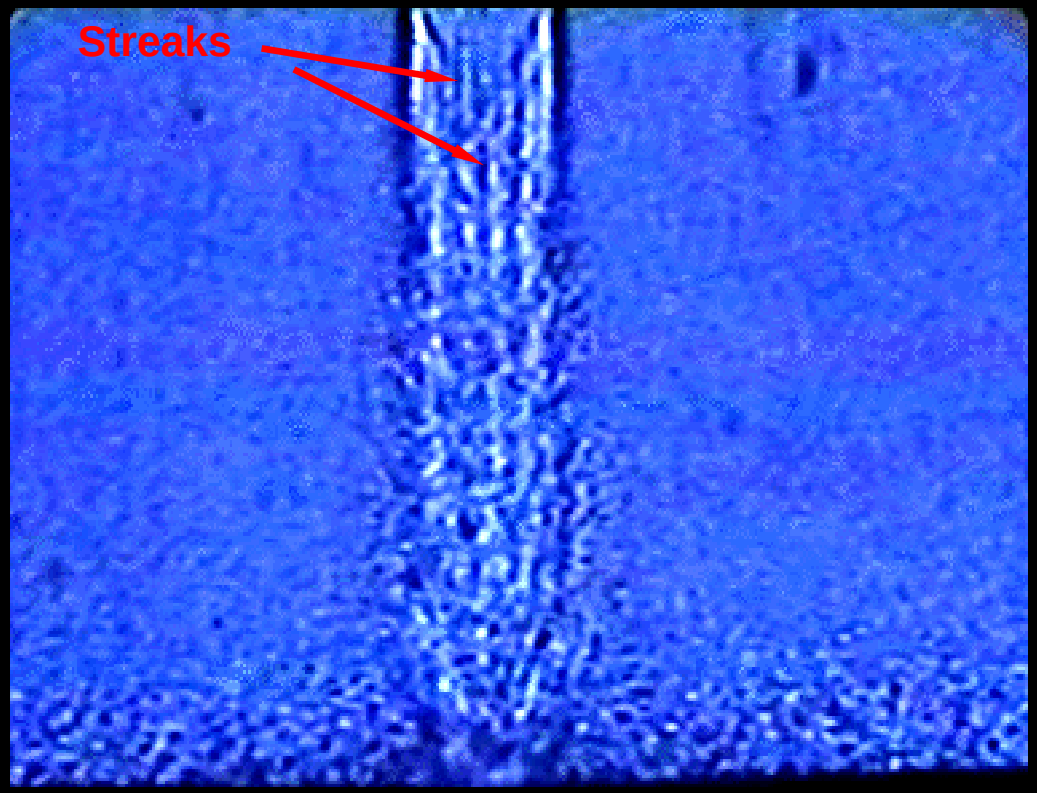
Phase-Averaged Shadowgraphs

M = 1.5 nozzle, NPR = 3.7

With Control



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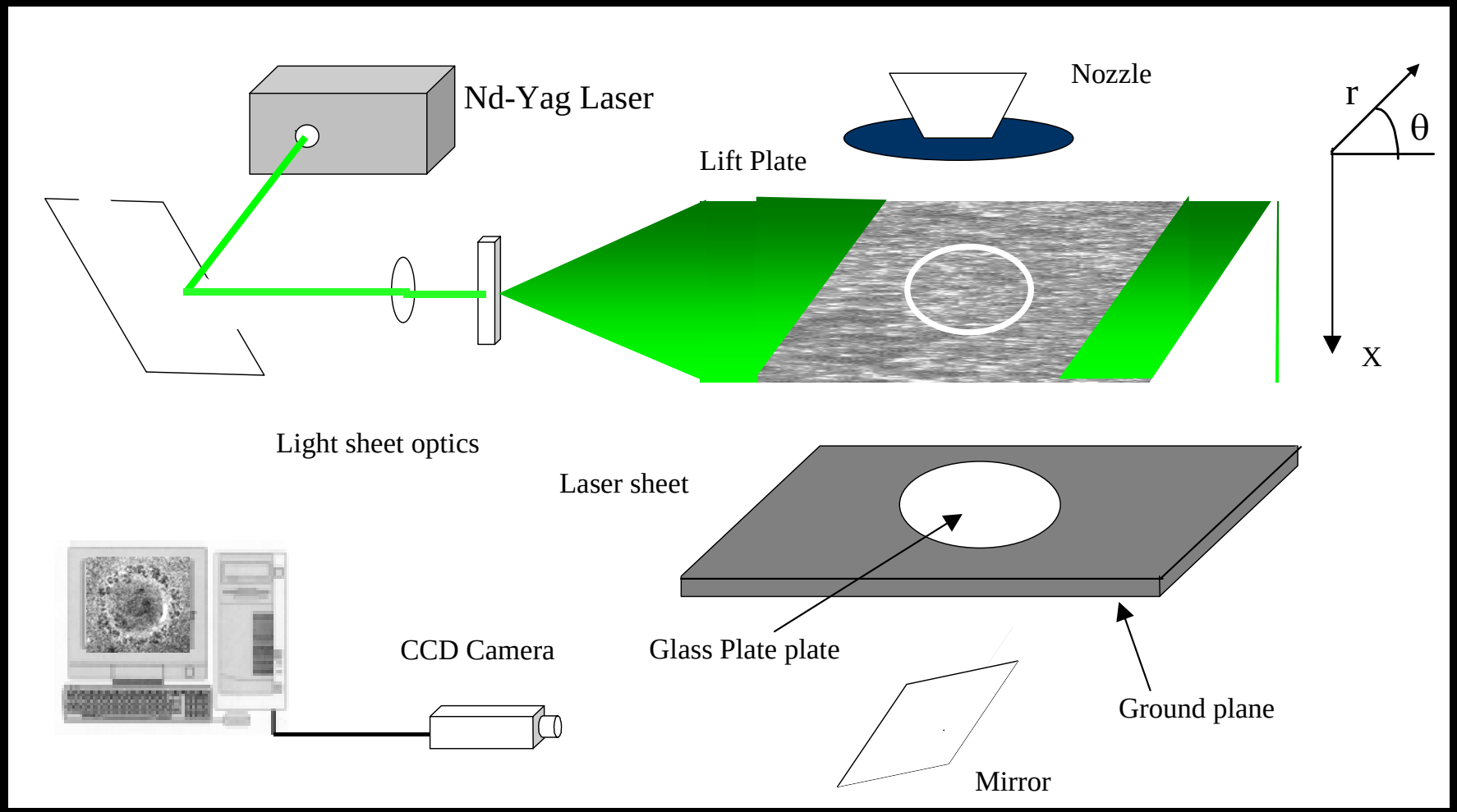
Cross Section PLS & PIV Setup



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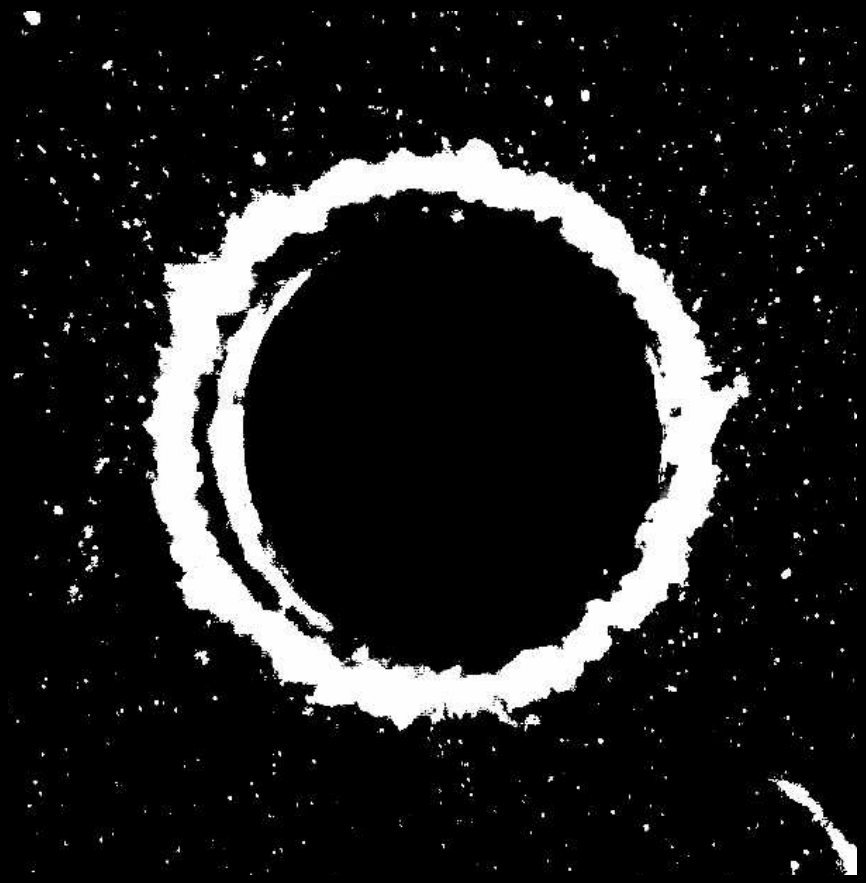
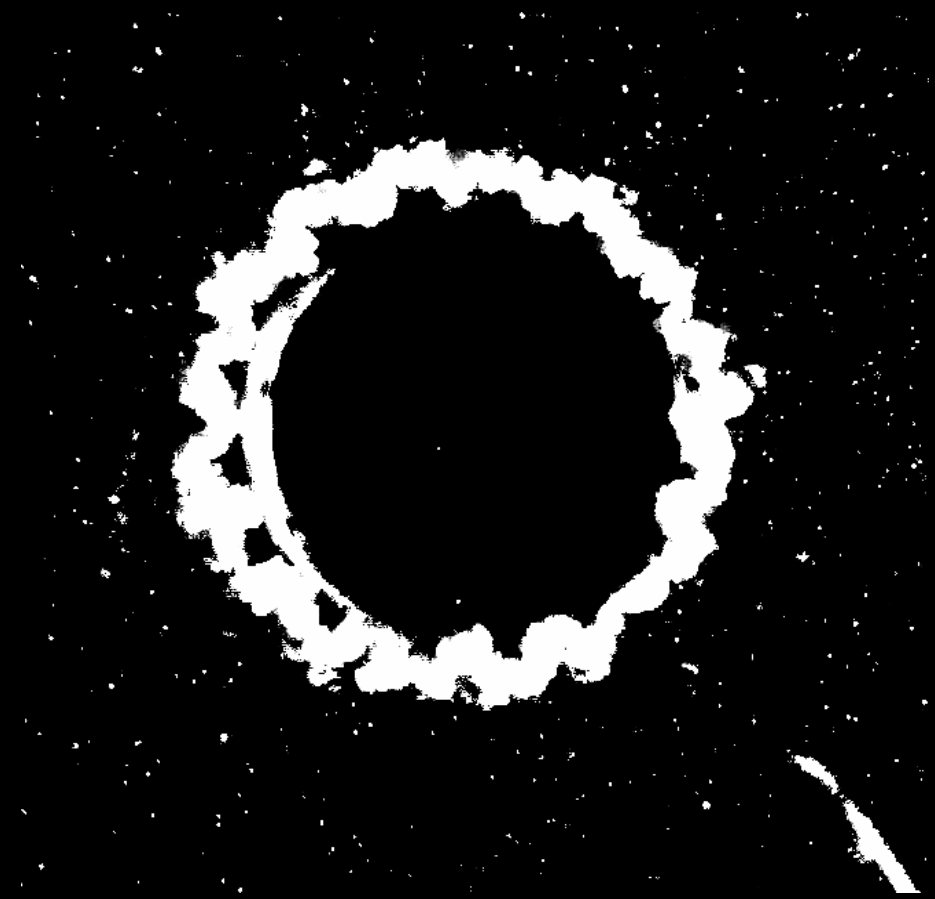
PLS Images, Averaged

NPR=5 h/D=4



No Control



With Control

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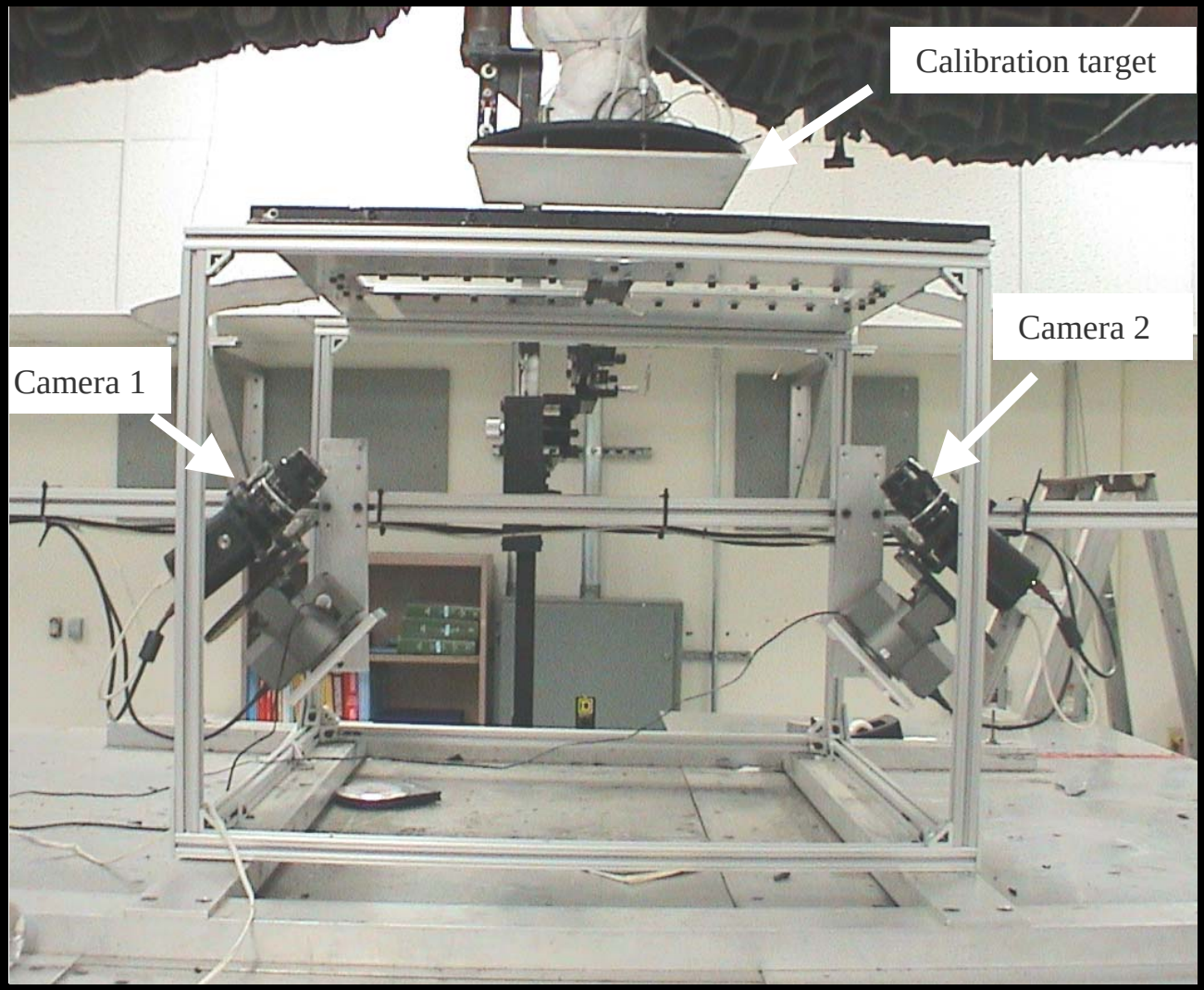
3D PIV Setup



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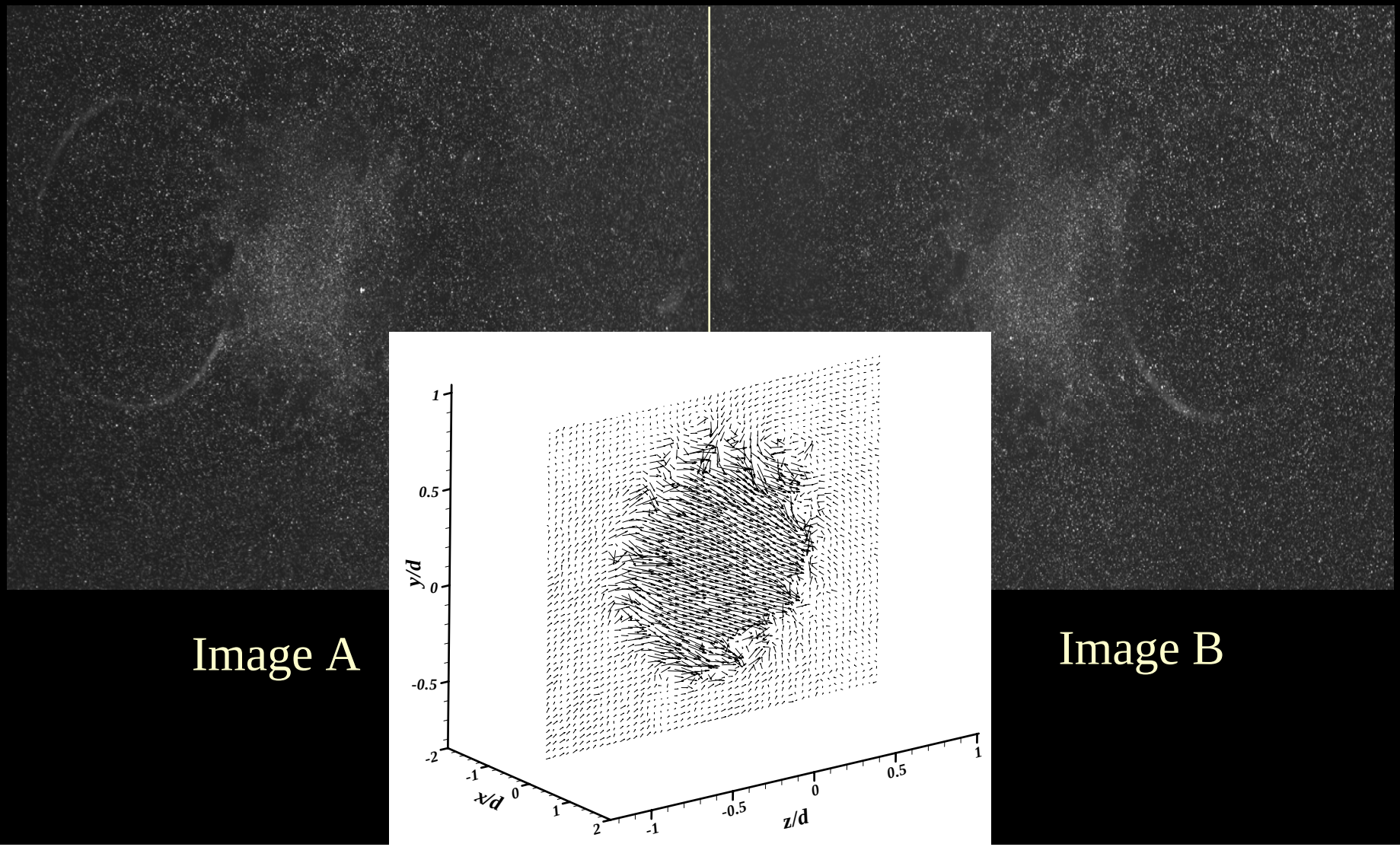
Instantaneous3D Images



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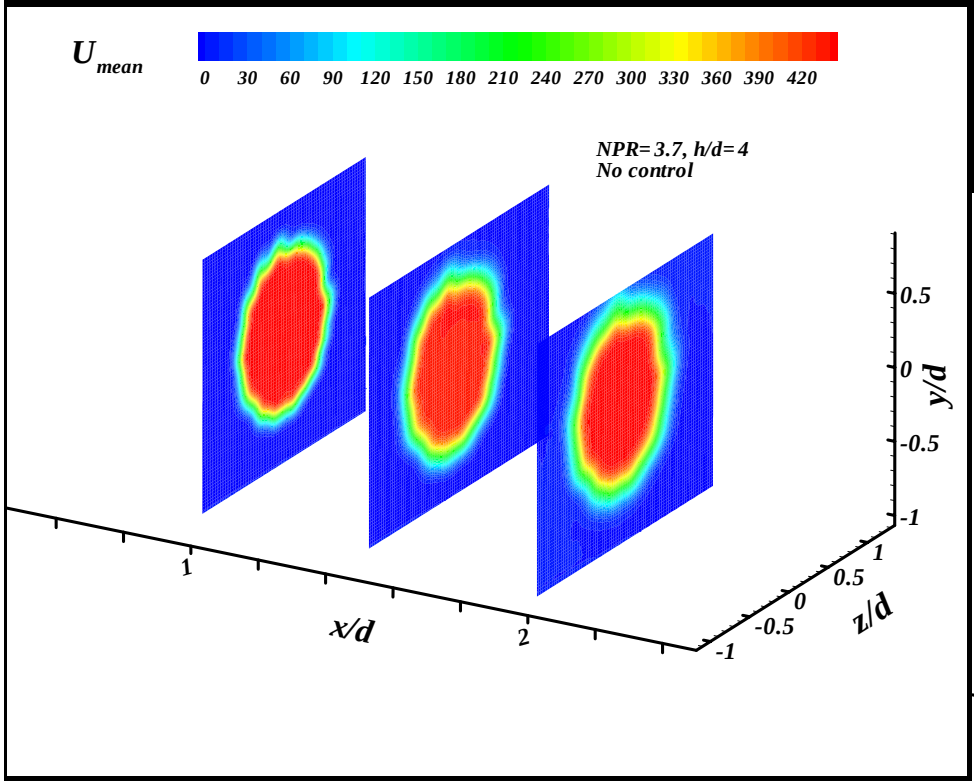
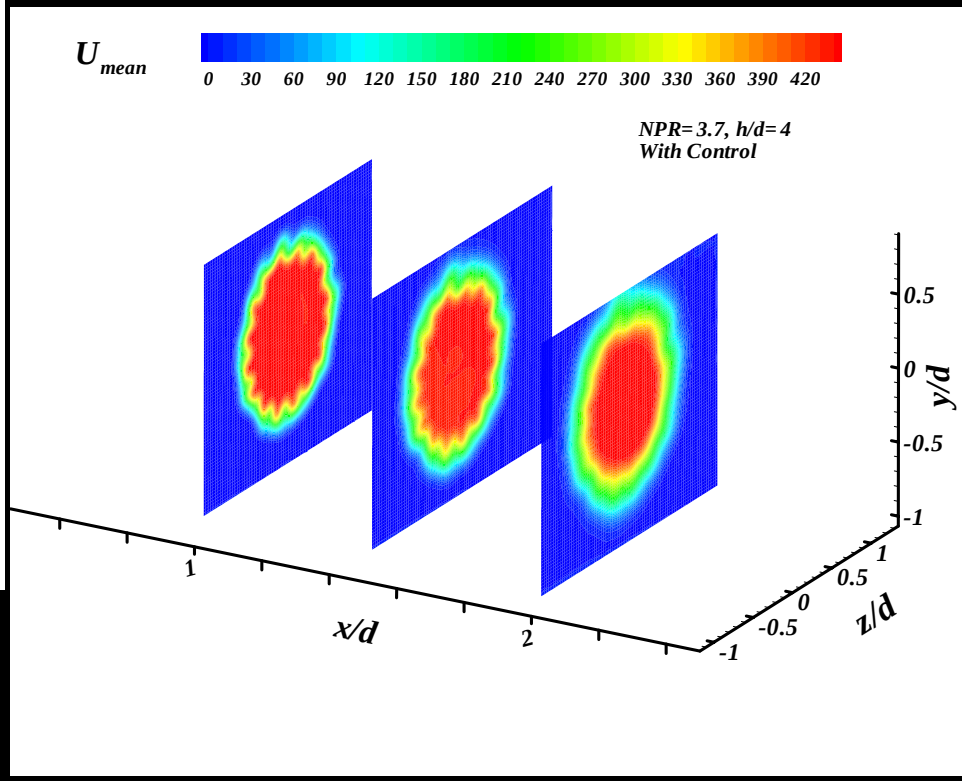
Effect of Microjet Control on Mean Axial Velocity

NPR=3.7, h/d=4, 90 deg. μjet



No Control

With Control



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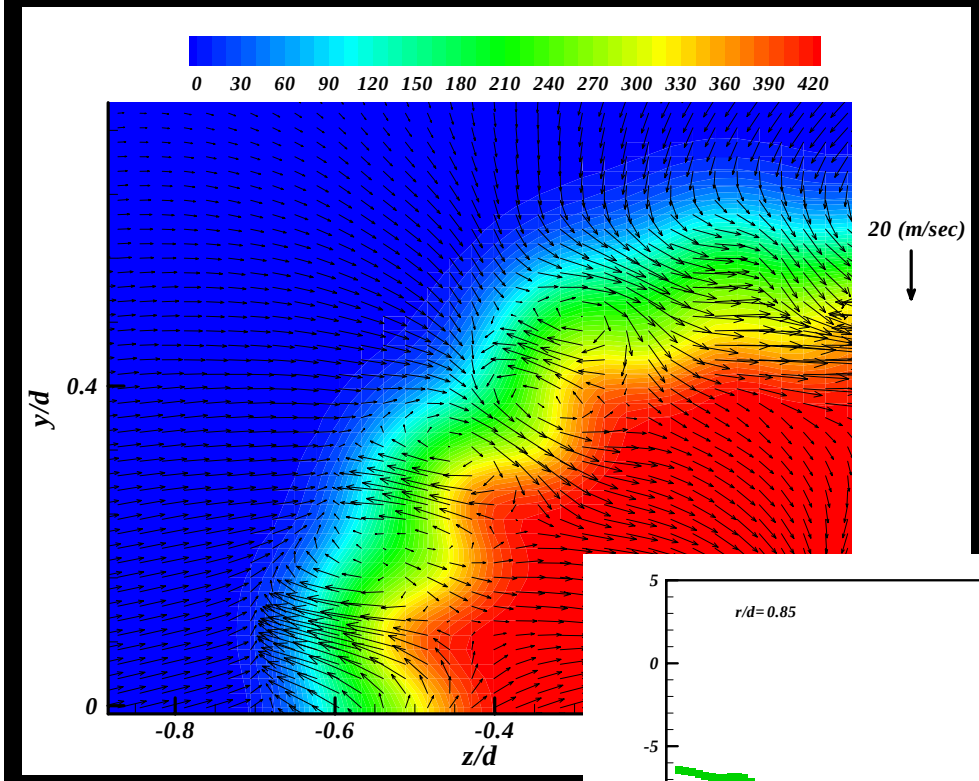
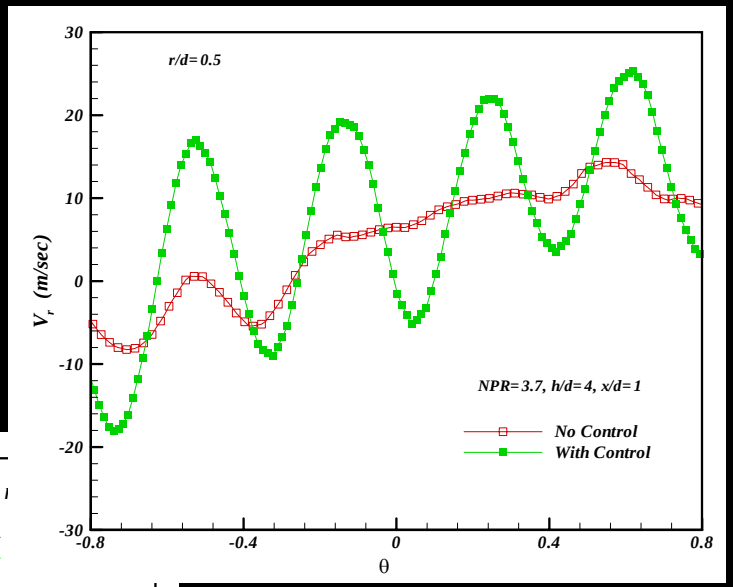
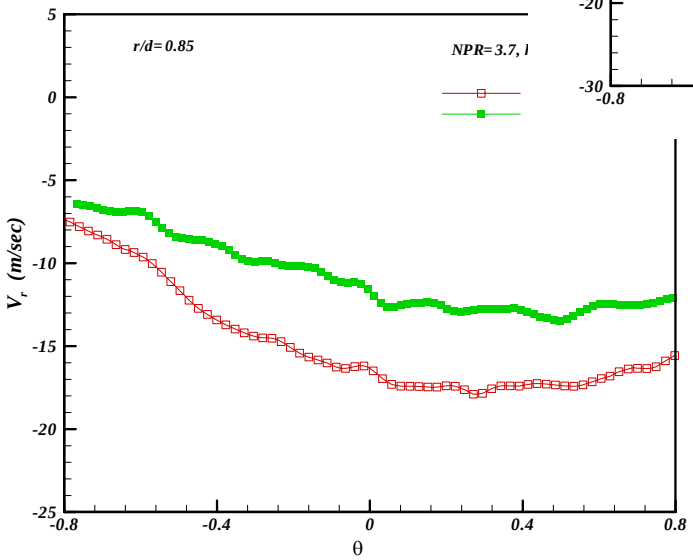
Close-up on Velocity Field

NPR =3.7, h/d = 4, x/d = 1







r/d=0.85

r/d=0.5

No Control
With Control

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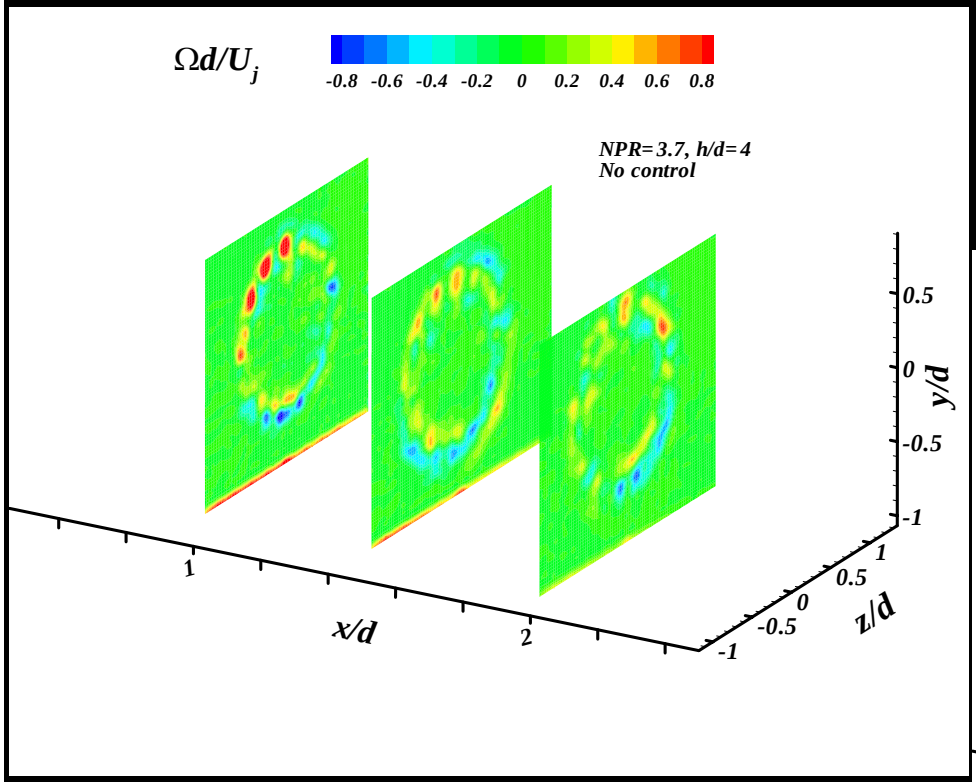
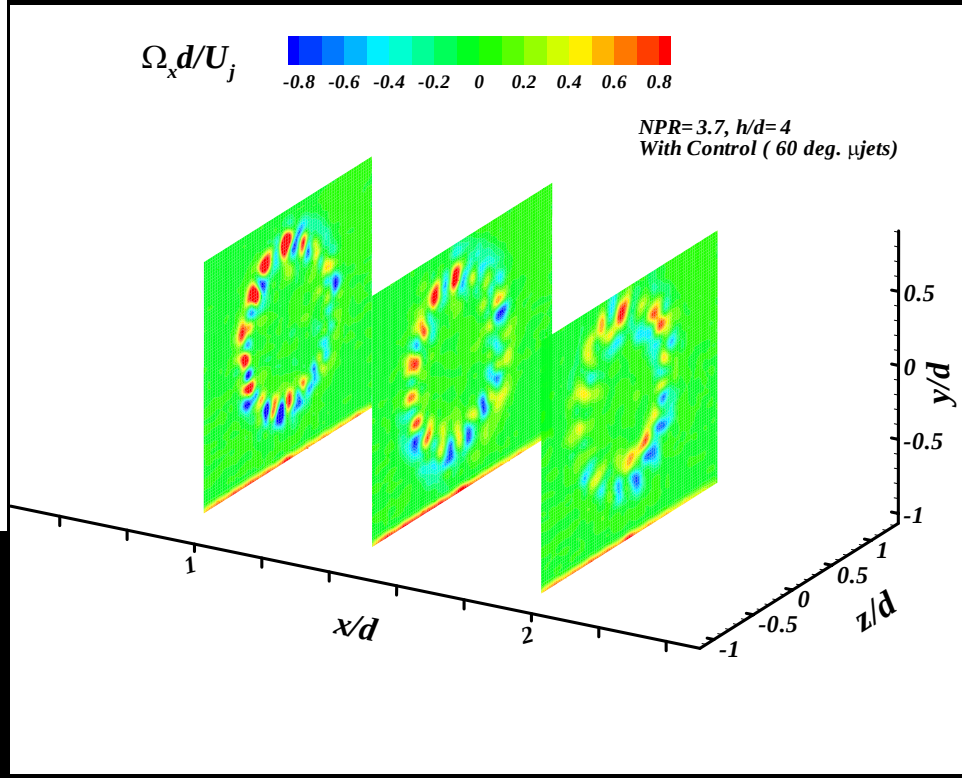
Effect of Microjet Control on Streamwise Vorticity

NPR=3.7, h/d = 4, 90 deg. μjets



No Control

With Control



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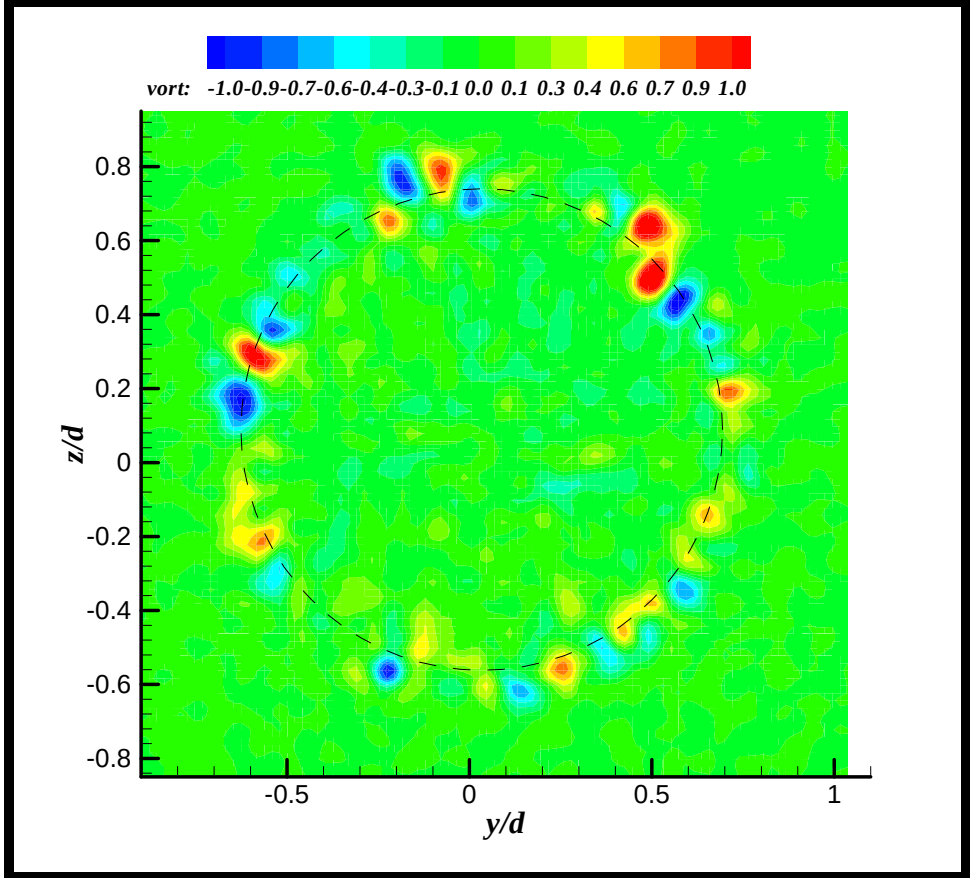
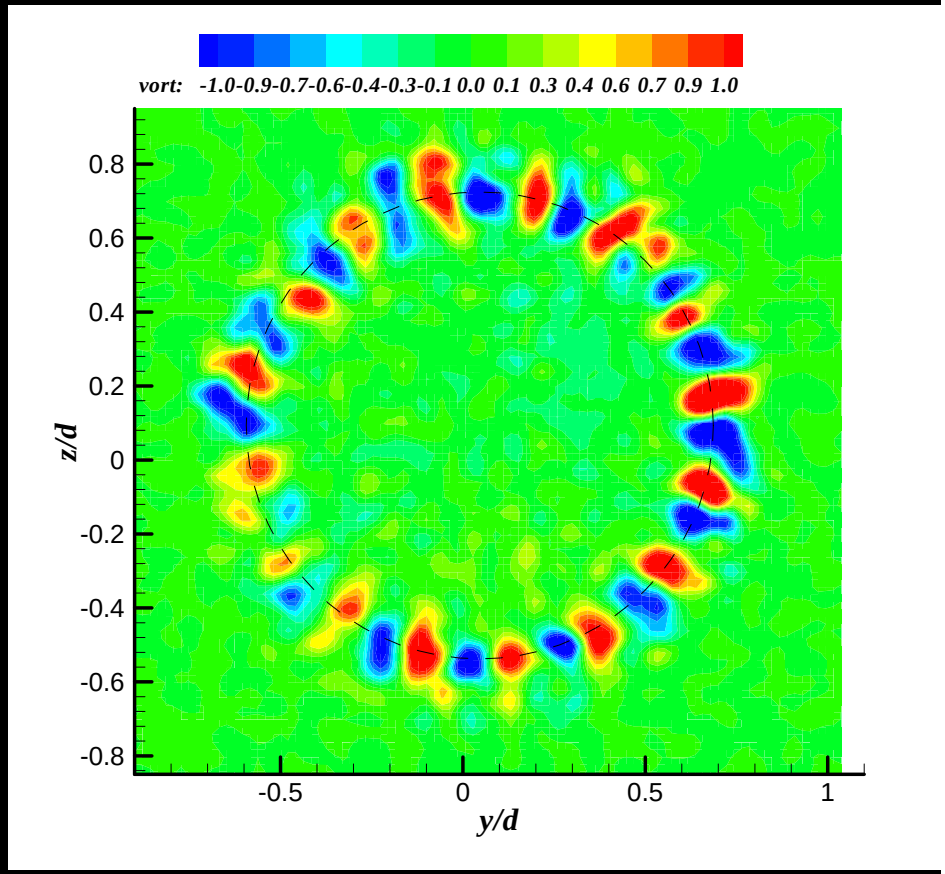
Effect of Microjet Control on Streamwise Vorticity

NPR=5, h/d = 4, x/d = 1, 90 deg. μjets



No Control



With Control

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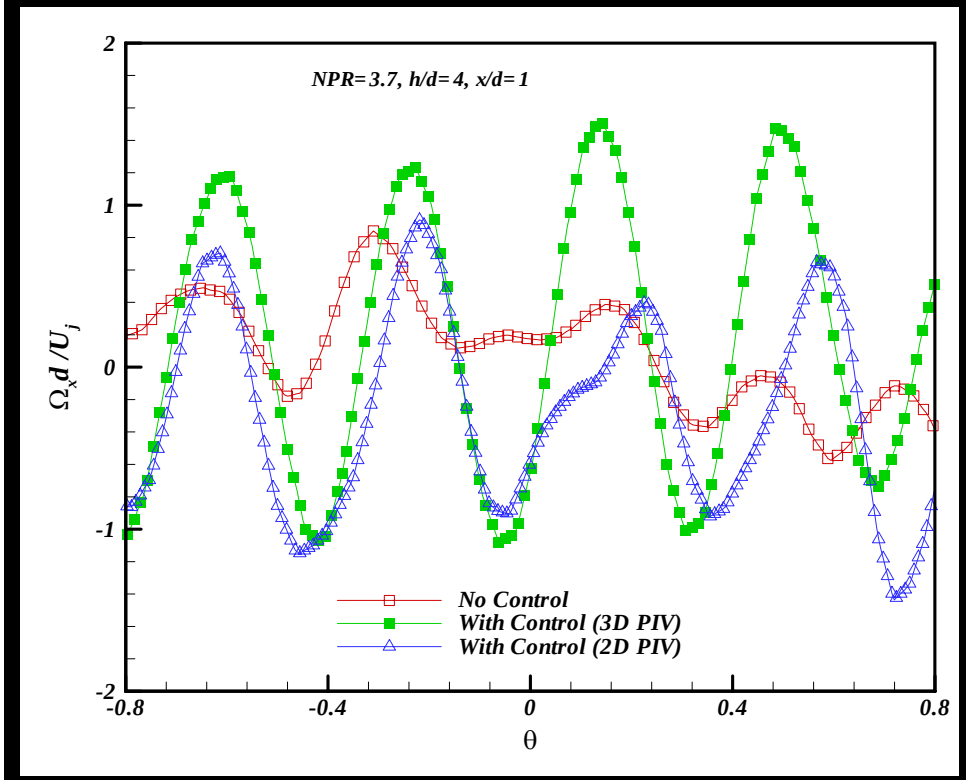
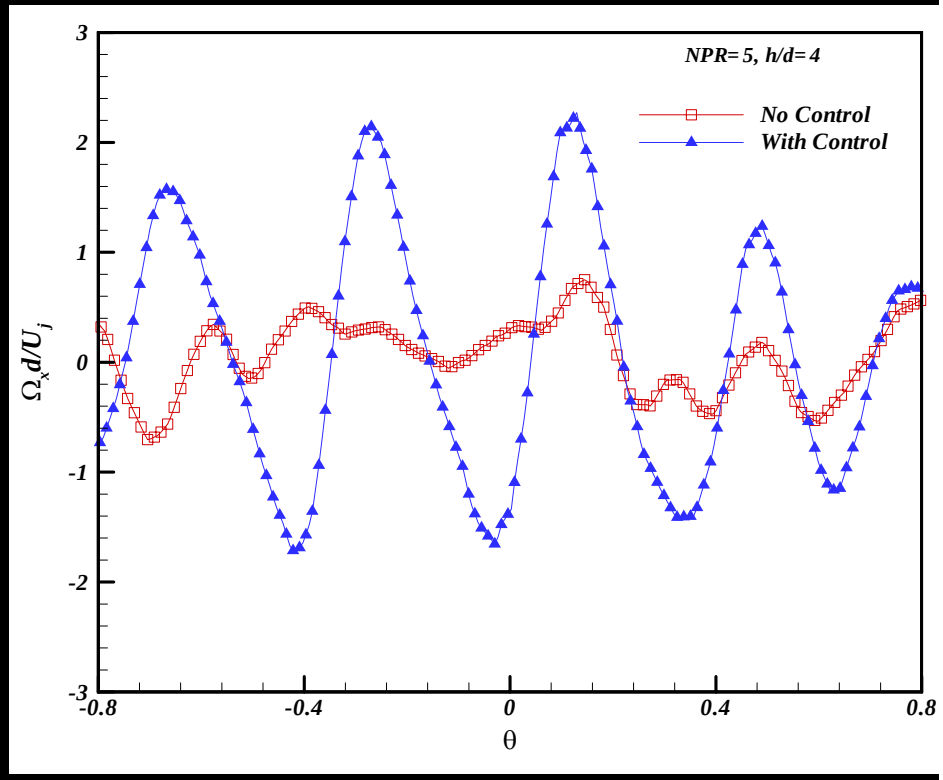
Effect of Microjet Control on Streamwise Vorticity

h/d = 4, x/d = 1, 90 deg. μjets

No Control
With Control (3D PIV)
With Control (2D PIV)





NPR = 3.7

NPR = 5

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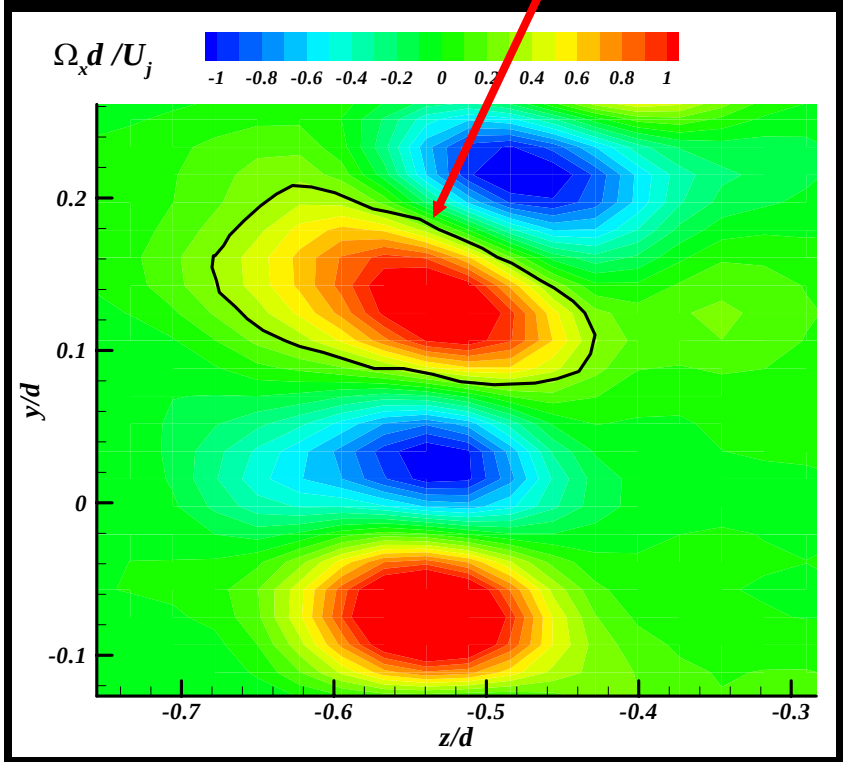
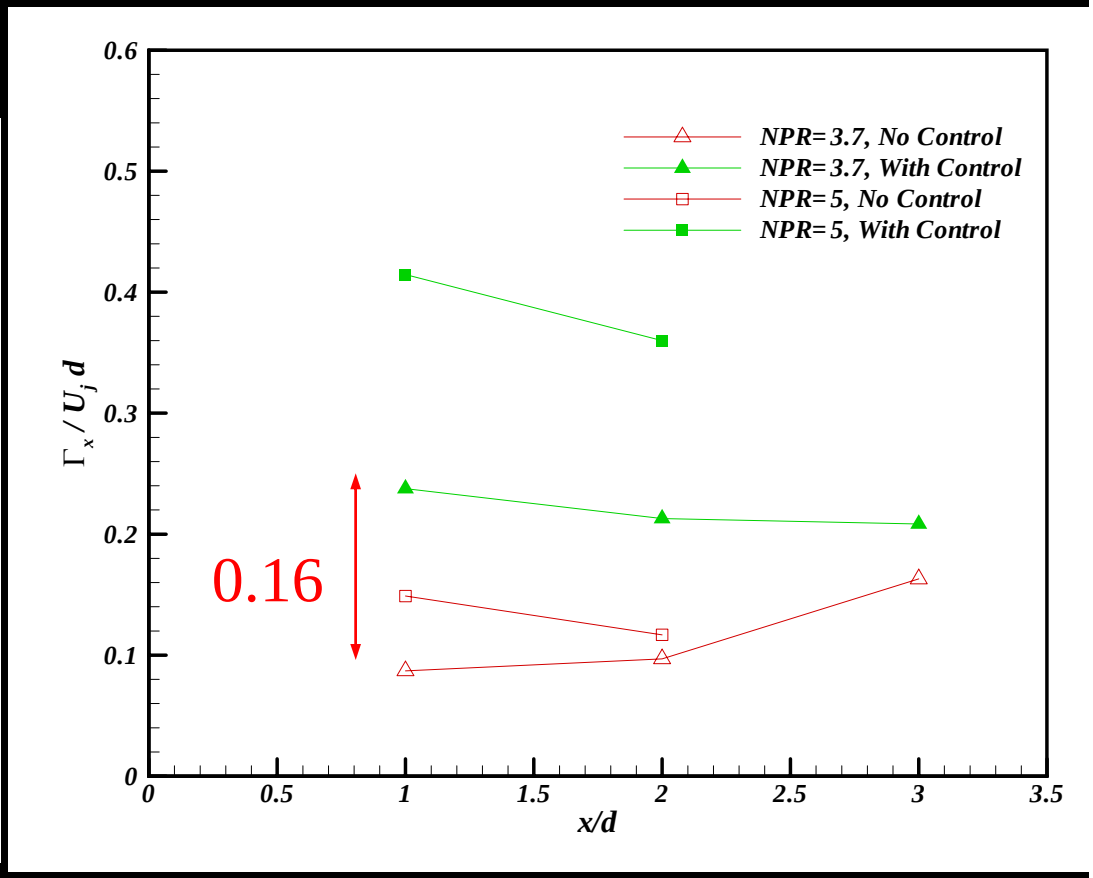
Streamwise Development of the Average Circulation

NPR=3.7 and 5, h/d = 4, x/d = 1, 90 deg. μjets

$$\Gamma = \int \vec{\Omega} \bullet \vec{n}\, dA$$





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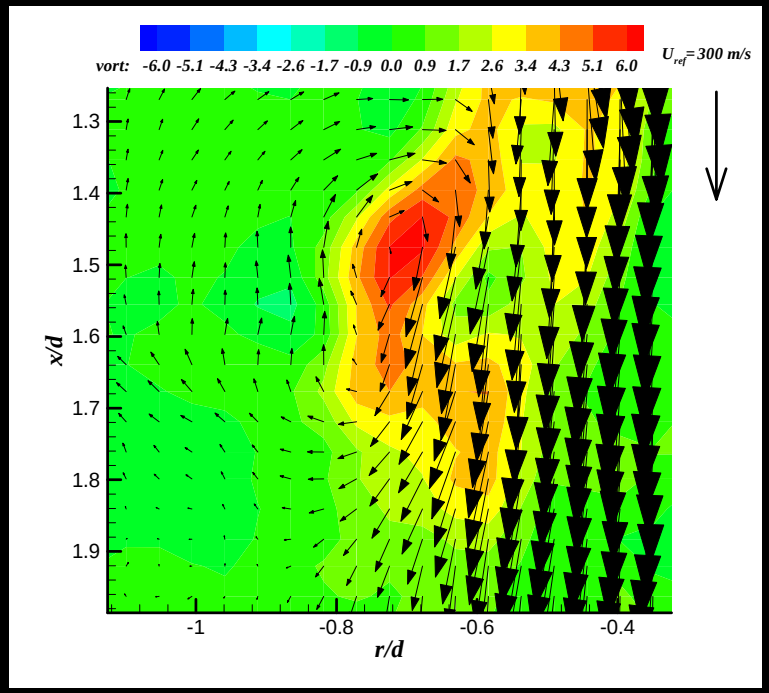
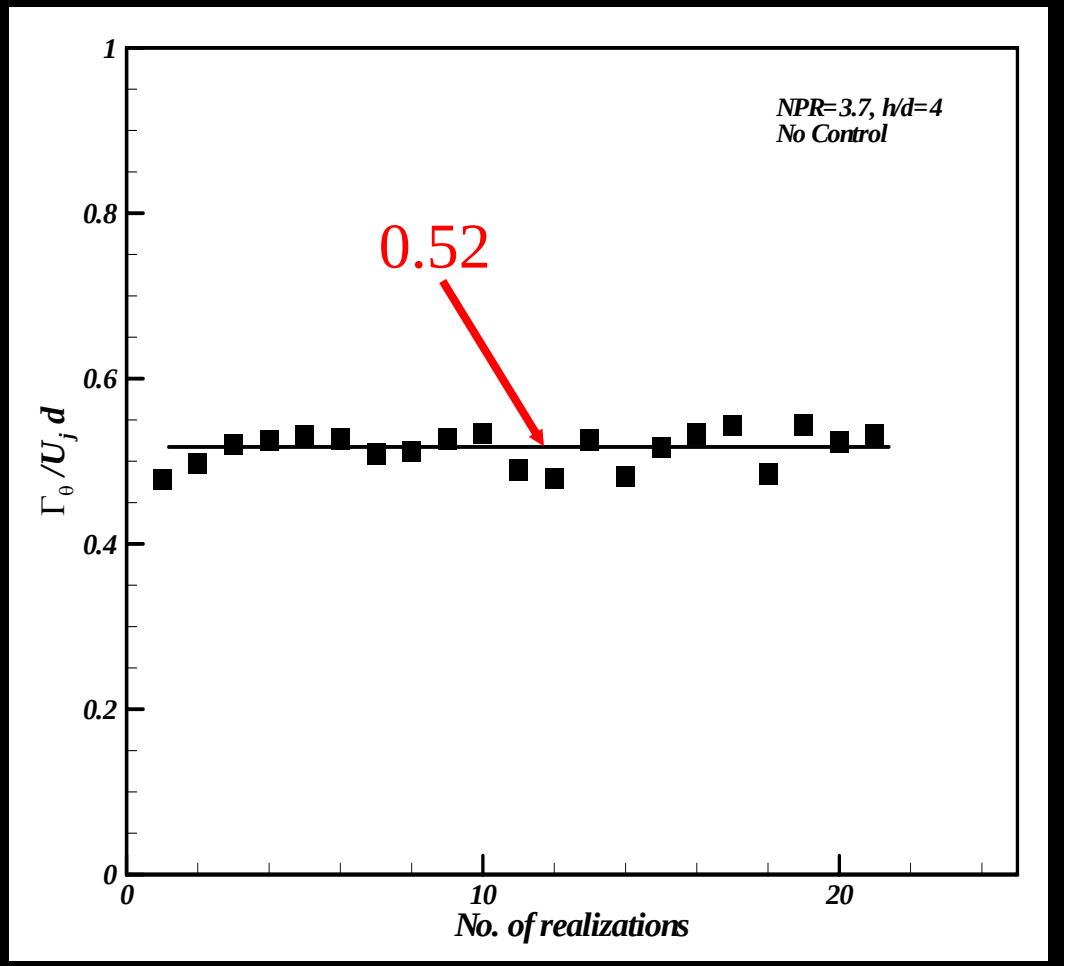
Circulation of Azimuthal Vorticity

NPR=3.7 h/d = 4, x/d = 1, 90 deg. μjets





For NPR=3.7

0.16/0.52 ≈ 31%

Streamwise Vorticity Formation Mechanism

Vorticity Transportation Equation:

Baroclinic torque

$$\frac{D\vec{\Omega}}{Dt} = \vec{\Omega}\cdot\nabla\vec{U} - \nabla\frac{1}{\rho}\times\nabla P + Stress\ term + \upsilon\nabla^2\vec{\Omega}$$

Streamwise vorticity component

$$\frac{D\Omega_x}{Dt} = \frac{\partial}{\partial x}\left(\frac{\partial\overline{u'v'}}{\partial z} - \frac{\partial\overline{u'w'}}{\partial y}\right) + \frac{\partial^2}{\partial y\partial z}\left(\overline{v'^2} - \overline{w'^2}\right) + \left(\frac{\partial^2}{\partial z^2} - \frac{\partial^2}{\partial y^2}\right)\left(\overline{v'w'}\right)$$

Streamwise Vorticity Formation Mechanism

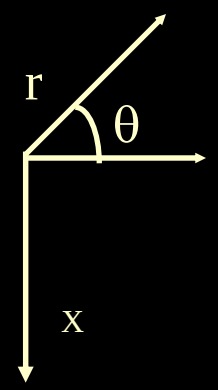
Vorticity Transportation Equation:

$$\frac{D\vec{\Omega}}{Dt} = \vec{\Omega} \cdot \nabla \vec{U}$$

Ω_x ***Streamwise vorticity***

Ω_r ***Radial vorticity***

Ω_θ ***Azimuthal vorticity***



Streamwise vorticity component

$$\frac{D\Omega_x}{Dt} = \underbrace{\Omega_x \frac{\partial U_x}{\partial x}}_{\text{Stretching}} + \underbrace{\Omega_\theta \left(\frac{1}{r}\frac{\partial U_x}{\partial \theta}\right) + \Omega_r \frac{\partial U_x}{\partial r}}_{\text{Tilting}}$$

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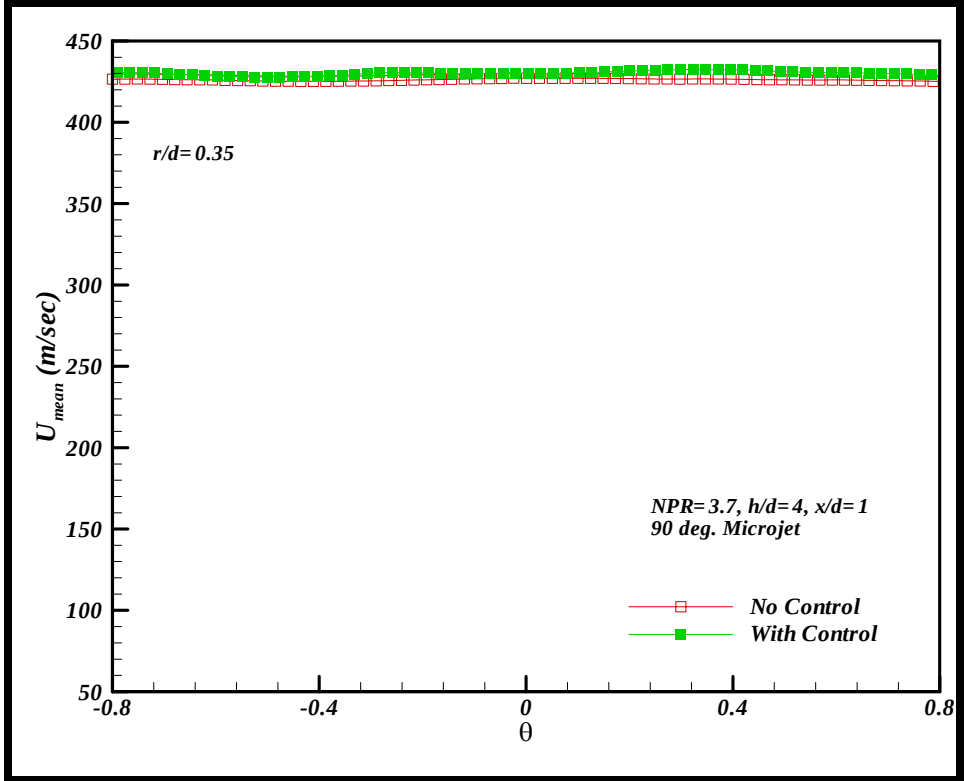
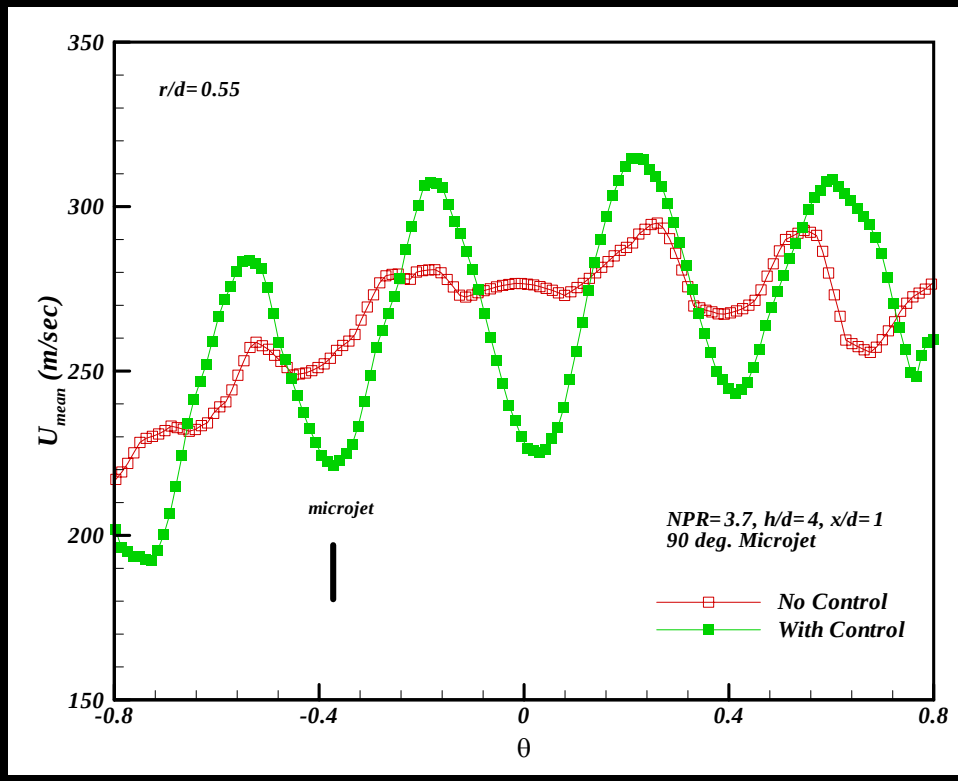
Titling of Azimuthal Vorticity

NPR=3.7 h/d = 4, x/d = 1, 90 deg. μjets

$$\Omega_\theta\left(\frac{1}{r}\frac{\partial U_x}{\partial \theta}\right)$$

No Control
With Control





r/d=0.35

r/d=0.55

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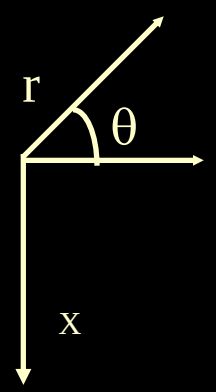
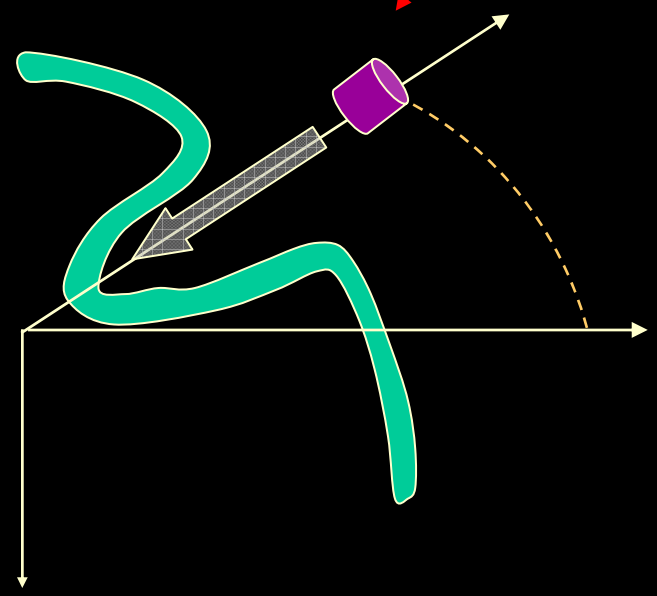
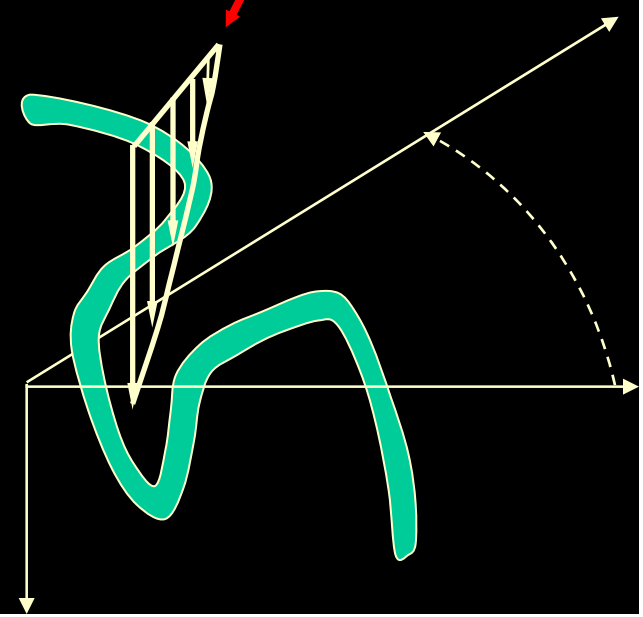
Titling and Stretching of Azimuthal Vorticity

$$\frac{\partial U_x}{\partial r}\Omega_r \rightarrow \frac{D\Omega_r}{Dt} = \Omega_\theta\left(\frac{1}{r}\frac{\partial V_r}{\partial \theta}\right) + \Omega_r\frac{\partial V_r}{\partial r} + \Omega_x\frac{\partial V_r}{\partial x}$$







Ω_x *Streamwise vorticity*

Ω_r *Radial vorticity*

Ω_θ *Azimuthal vorticity*

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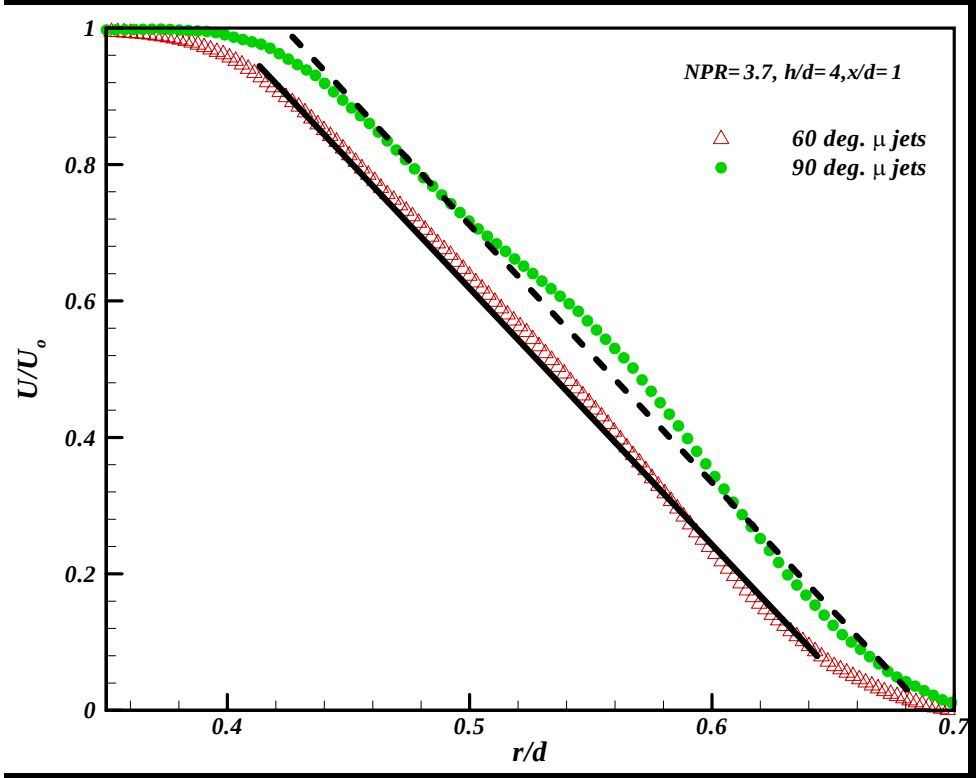
Effect of Microjet Angle

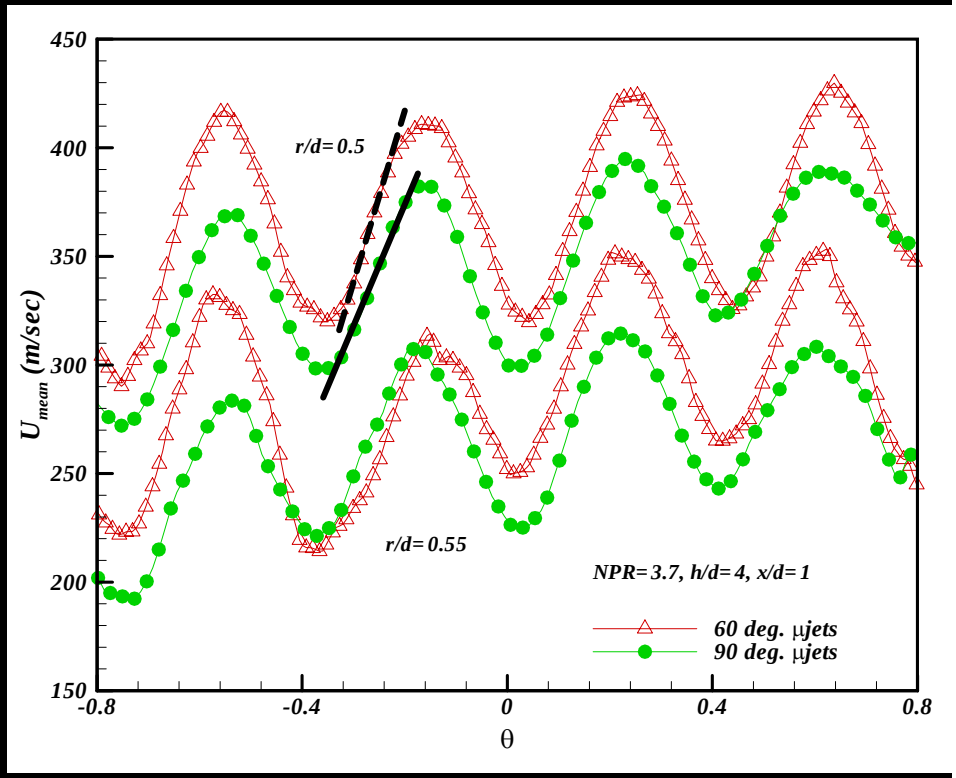
NPR=3.7 h/d = 4, x/d = 1, 60, 90 deg. μjets @ 100 psia

$$\frac{\partial U_x}{\partial r}$$

60 deg.
90 deg.

$$\frac{\partial U_x}{r\partial \theta}$$





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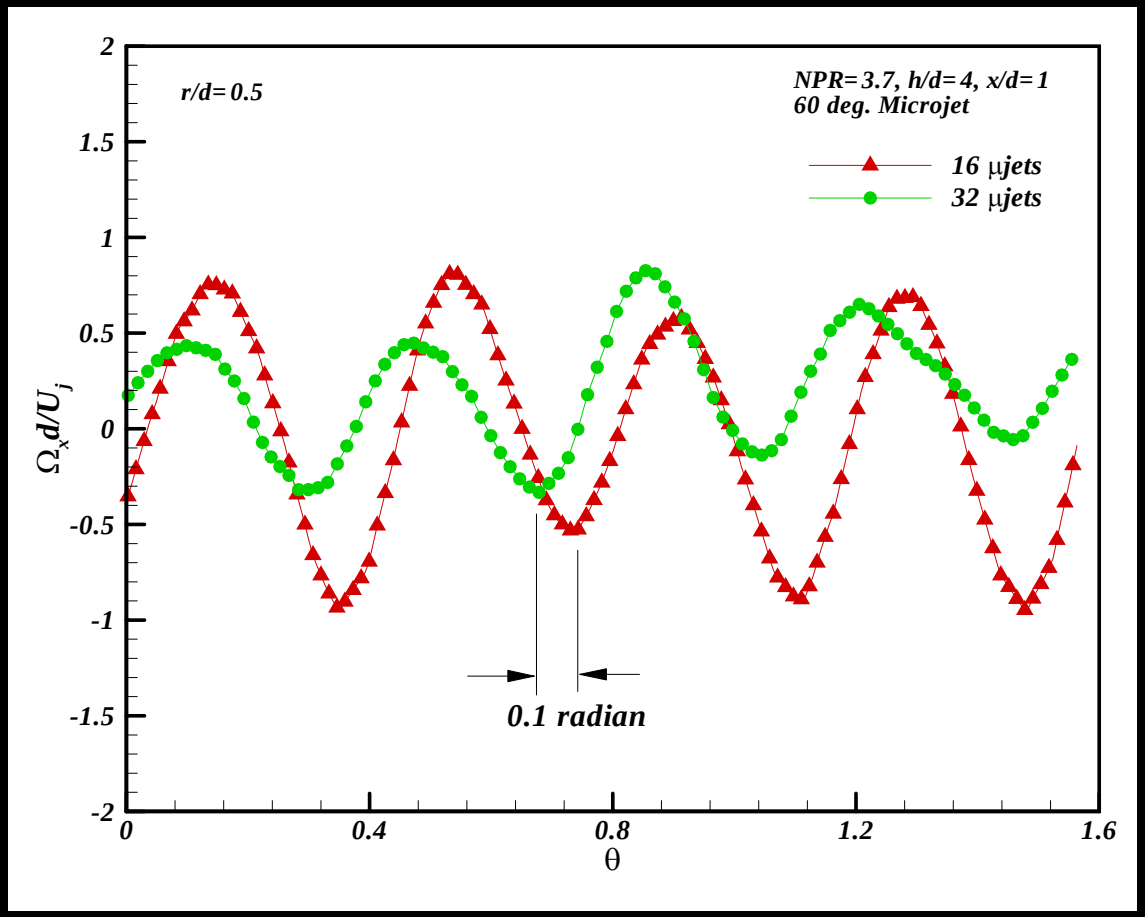
Effect of Microjet Spacing

NPR=3.7 h/d = 4, x/d = 1, 60 deg. μjets @ constant momentum



16 μjets

32 μjets

16 microjets, $\lambda_{3D} \approx 0.19d$

Widnall et al. (1974) and Tsai & Widnall (1976), $\lambda_{3D} \approx 0.23d$

Vorticity

Summary

- **Microjet control successfully disrupts the feedback loop and leads to:**
  - **Eliminate or significantly reduce the impinging tones**
  - **Reduce the overall sound pressure level**
  - **Reduce the unsteady loads**
- **PIV measurement clearly show microjet control:**
  - **Reduce in the azimuthal vorticity**
  - **Increase in the streamwise vorticity**
  - **Thicken the shear layer at nozzle exit**
- **The plausible mechanism of microjet control -**
  ***Redirect the azimuthal vorticity into streamwise direction through*:**
  - **Tilting**
  - **Stretching**

Thank you !!!