# Momentum and Scalar Mixing Across Jet-fluid Interface of Submerged Rectangular Jet

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**Abstract:** Submerged jets are used in widespread engineering applications, such as chemical reactors, combustion chambers, and ocean outfalls. While the round jet, being the commonest form of submerged jets in practice, has been extensively studied, the rectangular jet is of research interests in the sense that it approximates the ideal two-dimensional (2D) flow geometry.

In this study, the mixing behavior across the jet-fluid interface of a rectangular jet is investigated experimentally with particle image velocimetry (PIV) and laser-induced fluorescence (LIF). The objectives are to understand the inter-relationship between mixing of momentum and dilution of scalar species concentration in a rectangular jet discharging into a stagnant environment. The submerged rectangular jet was placed into a large water tank to avoid boundary effects, with $Re \approx 4500$ to produce turbulent flow at the nozzle exit. The aspect ratio (AR) was 10 to approximate a 2D flow. Conventional statistics of the velocity and scalar concentration data were performed to investigate the global jet behavior, including flow regimes and self-similarity features. Meanwhile, instantaneous data at several points along the jet-fluid interface were observed and analyzed in order to investigate the correlation between concentration and velocity fluctuations in local region. The results show that for the region near the exit (2 to 2.5D, D being jet exit height), velocity and concentration fluctuations are influenced by vortex motions symmetrically across the jet. Beyond 2.5D, co-presence of large-scale concentration and radial velocity fluctuations are found to be not symmetric across the jet, which occurs only on one side of the jet.

* Presenter

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# Wastewater discharge

- Wastewater is often discharged into receiving waters by submerged jet;
- Previous researches mainly focus on submerged round jets;
- Rectangular jets can approximate the ideal two-dimensional (2D) flow geometry is of fundamental interests to wastewater discharge;

Source: http://www.amazfacts.com

Source:http://www.pavingexpert.com/edging5.htm

# Previous Works

- W.R.Quinn(1992) & Zaman(1999): For rectangular jets, the aspect ratio (*AR*) influences the jet turbulent mixing process
  - $AR = L/D$, where *L* and *D* are the long and short sides of rectangle;
  - Rectangular jets with large *AR* can be considered Quasi-2D;

- Mi. et al.(2005): Rectangular jet can divided into three distinct zones (AR>15):
  - (I) Initial quasi-2D region (plane-jet-like);
  - (II) Transition zone;
  - (III) Final quasi-axisymmetric region
  - Even $AR = 10$, **Half-Power-Law Decay** Region (I) can be observed.

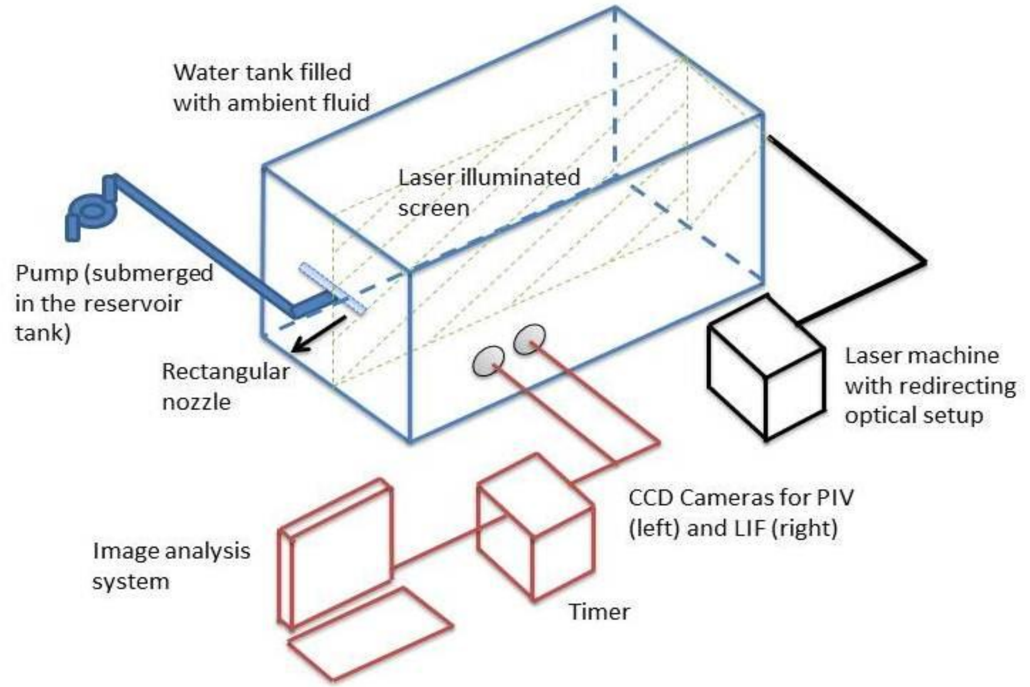
# Objectives

- To verify half-power-law decay region can be observed for rectangular jet with AR=10
- To characterize the mixing properties, including both momentum and scalar species spreading across the interface between the flow and its ambient fluid;
- To enhance outfall designers understanding on turbulent rectangular jet mixing.

# Experimental Setup

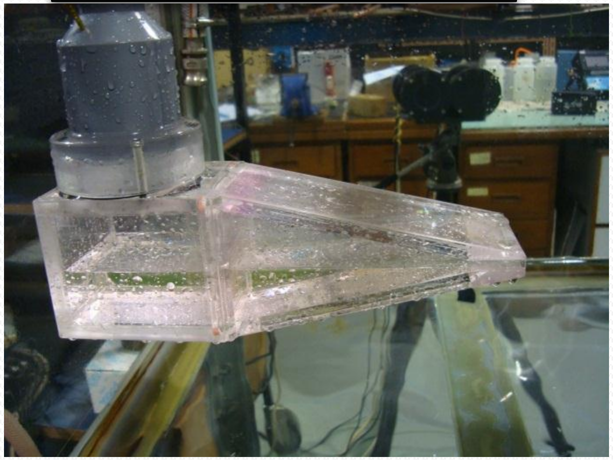
- Concentration Measurement – Laser Induced Fluorescence (LIF)
  - The selected fluorescent tracer can absorb laser light energy and emits a light with longer wavelength;
  - Background and contrast are corrected
  - Concentration is captured and represented as pixel grayscale;

- Velocity Measurement – Particle Image Velocimetry (PIV)
  - Two successive images of seeding particles are captured by another CCD camera at a known time interval $\Delta t$;
  - Particle Velocity $V=\frac{\Delta S}{\Delta t}$, where $\Delta S$ is the displacement of the particle;



# Experimental Setup

Rectangular Nozzle



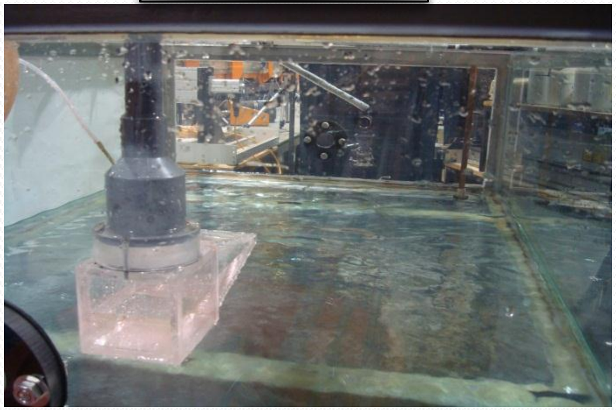
Length $L$ = 75 mm

Height $D$ = 7.5 mm

$AR$ = 10

Flowmeter

Water Tank



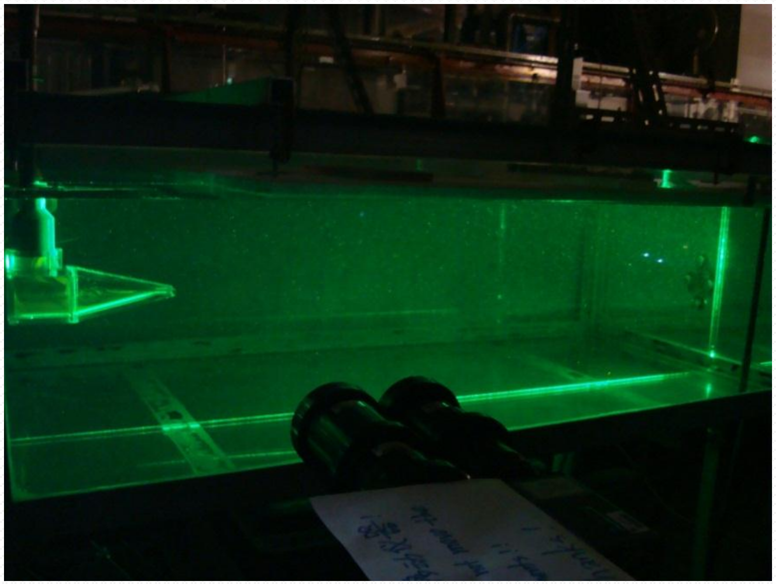
Length = 1.8 m

Width = 1.2 m

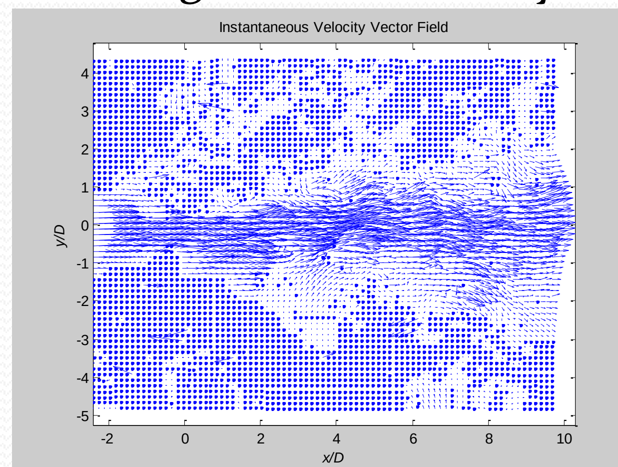
Height = 0.5 m

CCD Cameras

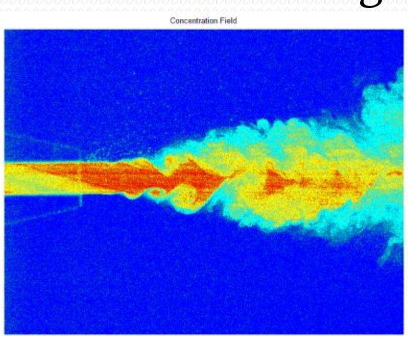
# Experimental Setup

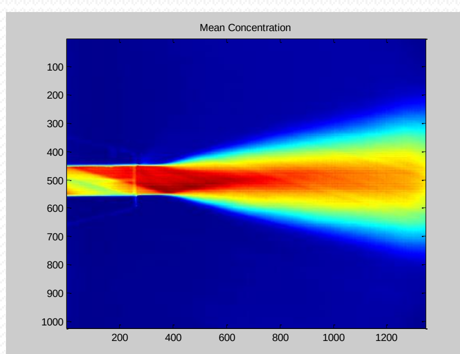


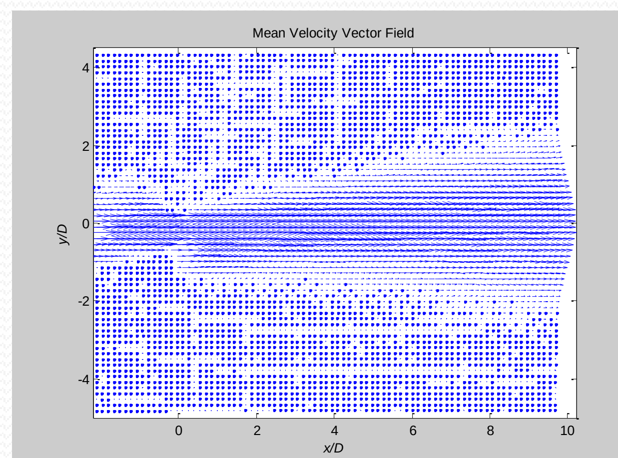
Typical PIV Images – Instantaneous
– Time-Averaged Mean Velocity Vector Field




Typical LIF Images – Instantaneous
– Time-Averaged Mean Concentration



# Experiment Settings

Experiments were performed with the following conditions and settings:

- Flow rate: 1200 L/hour, corresponding to an exit velocity of $U_0$=0.6 m/s.

- $Re = \frac{D\,u_0}{\nu} \approx 4500\ (>4000)$

Labus and Symons (1972): In most cases, provided the Reynolds number exceeds 2000 the jet flow will be turbulent. However, to reach a fully developed turbulent flow state, Reynolds number should be around 4000.

- Range of capture: 0 – 10*D*

# Analysis and Results

- Conventional Statistics
  - Flow field division;
  - Self similarity

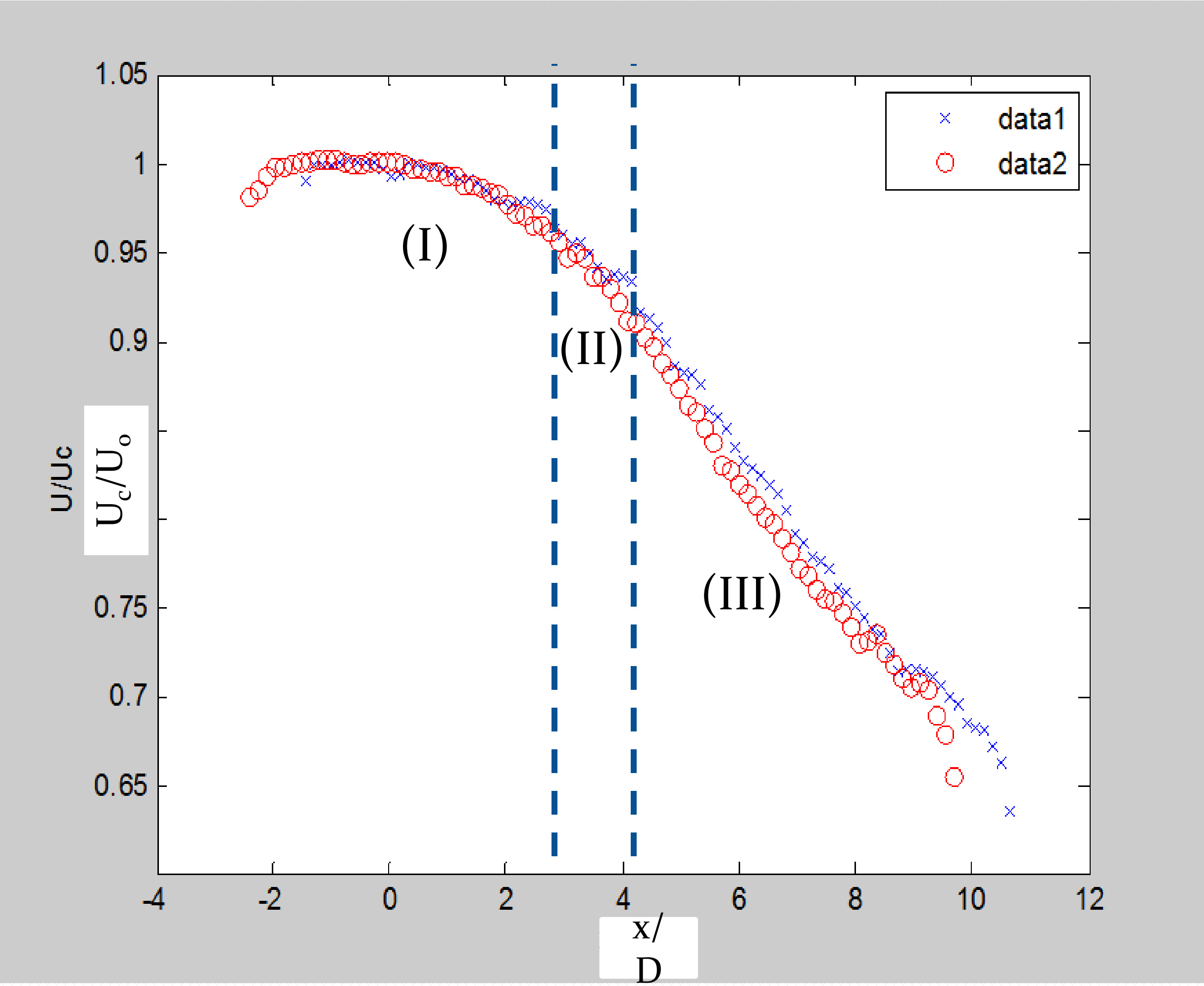
- Conditional Sampling
  - Samples concentration data from instantaneous results that met specific local requirements;
  - Correlates the local concentration profiles to velocity fluctuations.

# Conventional Statistics

- Fluctuation calculations
  - *u'*, *v'*, and *c'* are the standard deviations of *U*,*V*, and *C*, respectively

| $\overline{c'c'}$ | $\overline{u'u'}$ | $\overline{v'v'}$ | $\overline{u'v'}$ | $\overline{u'c'}$ | $\overline{v'c'}$ |
|---|---|---|---|---|---|
| Concentration Variance | Axial Normal Stress | Radial Normal Stress | Shear Stress | Axial Turbulent Flux | Radial Turbulent Flux |

# Centerline Mean Velocity Decay

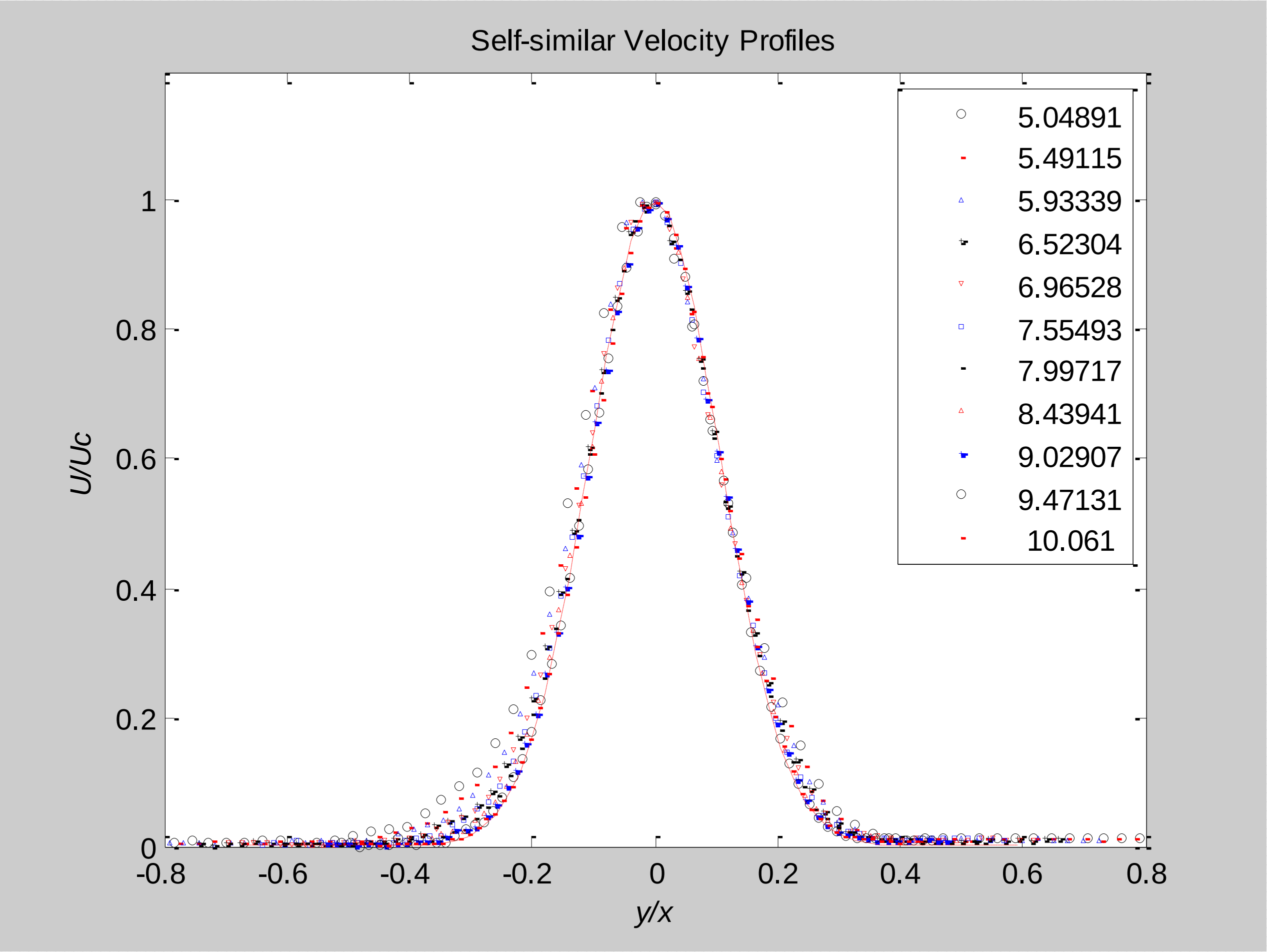



Region (I): 0-2.2*D*
Potential Core

Region (II): 2.2-3.7*D*
Transitional

Region (III): 3.7-10*D*
Half-Power-Law
Decay
($U_c \sim x^{-1/2}$, Quasi-2*D*)

# Self-similar Velocity Profiles




$$U(x,y) = U_c\, e^{-\left(\frac{y}{b_u}\right)^2}$$

Velocity half width

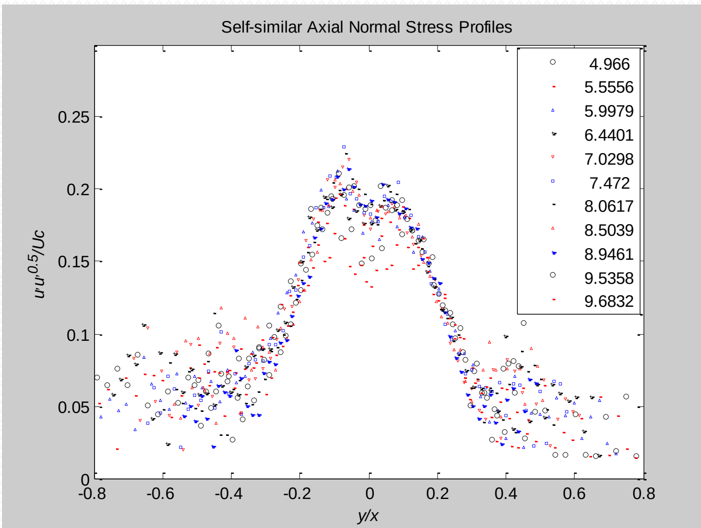
$b_u = 0.155\, x$

Round jets: $b_u = 0.107x$

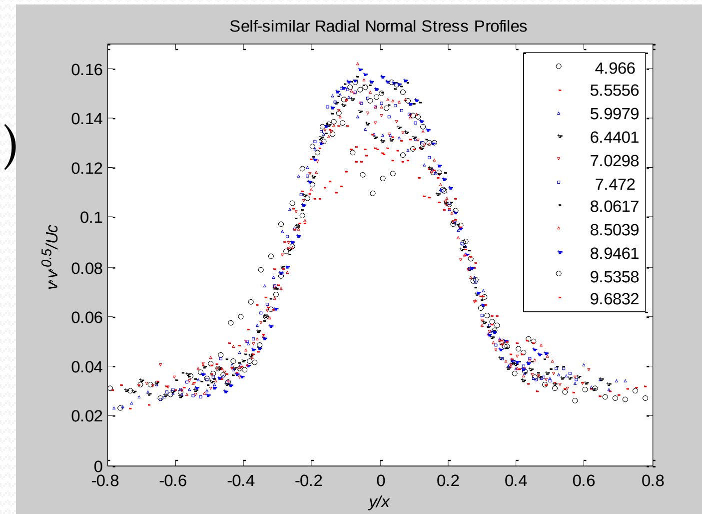
Plane jets: $b_u = 0.116x$

# Self-similar Stress Profiles

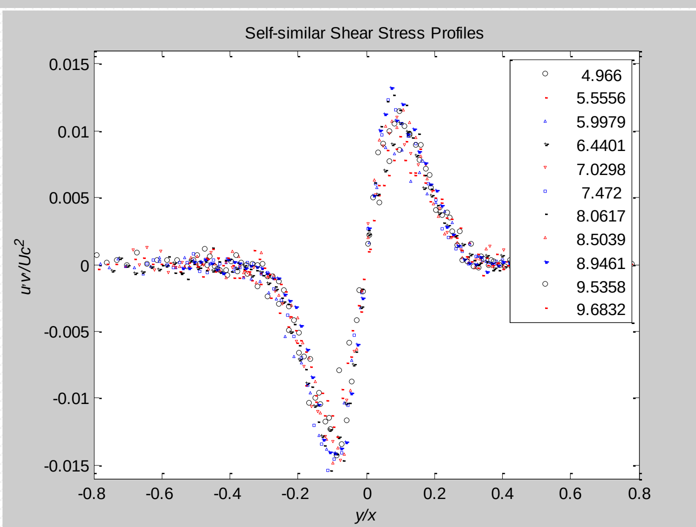
(A)




(B)

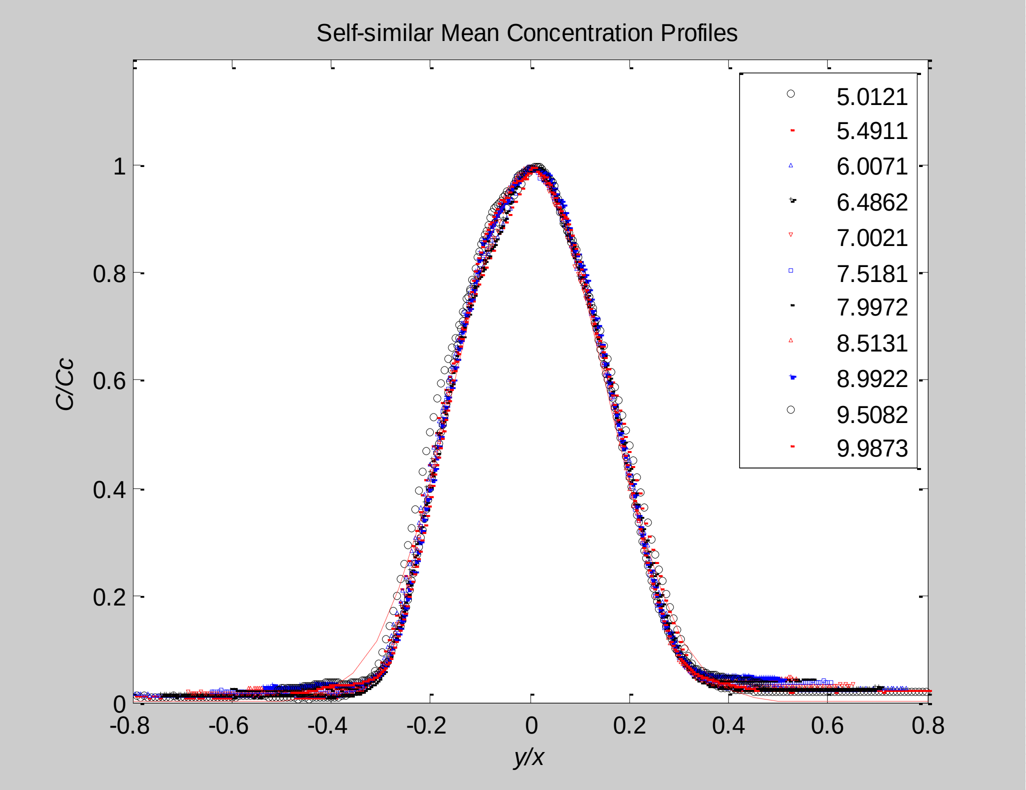



(C)




(A) Axial Normal Stress
(B) Radial Normal Stress
(C) Shear Stress

# Self-similar Concentration Profiles




$$C(x,y) = C_c\, e^{-(\frac{y}{b_c})^2}$$

Concentration half width
$b_c = 0.207x$

Round jets: $b_c = 0.127x$
Plane jets: $b_c = 0.157x$

$$\frac{b_c}{b_u} = 0.207/0.155 = 1.34$$

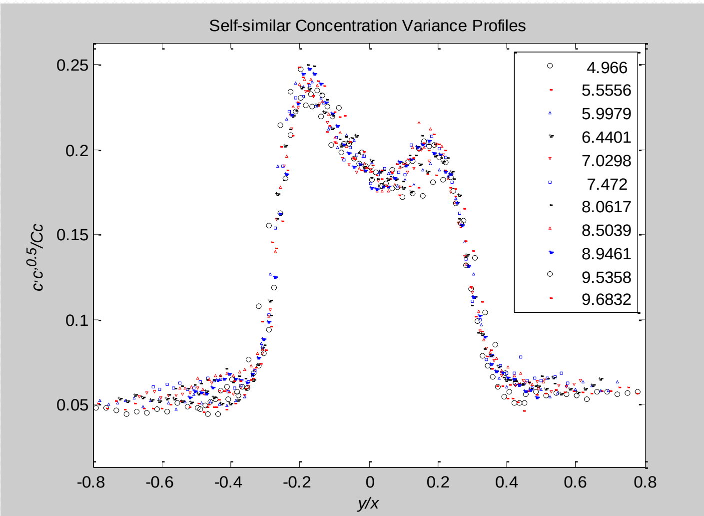
Plane jets (Fischer et al. 1979) :

$$\frac{b_c}{b_u} = 1.35$$

**Concentration field spreads 34% faster than the velocity field**

# Self-similar Concentration Variance Profile and Turbulent Flux Profiles

(A)

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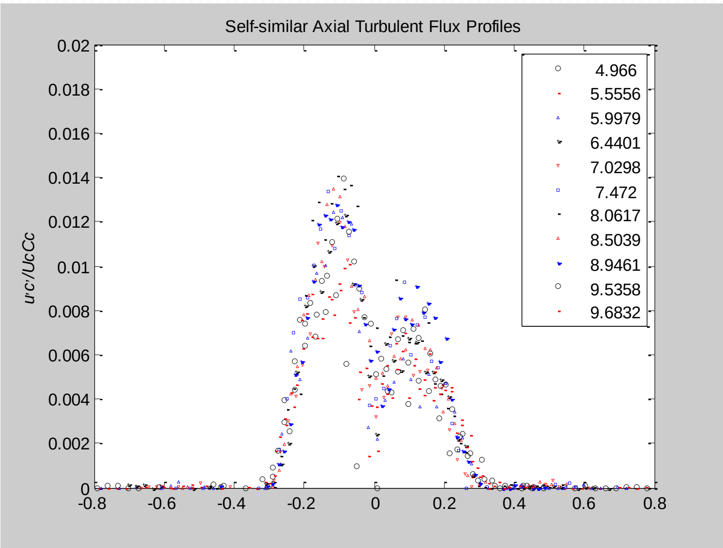
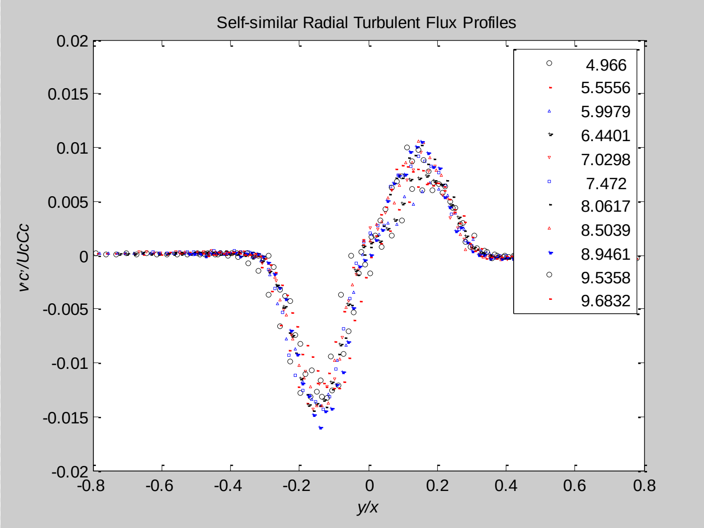


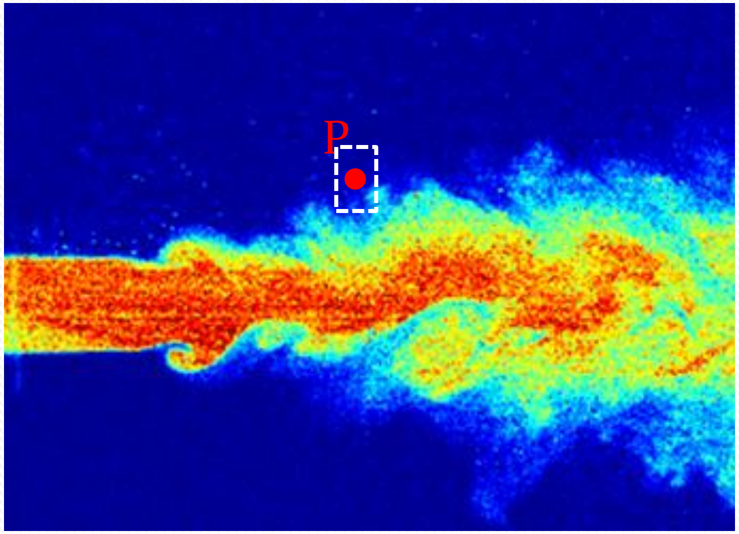

(C)




(A) Concentration Variance
(B) Axial Turbulent Flux
(C) Radial Turbulent Flux

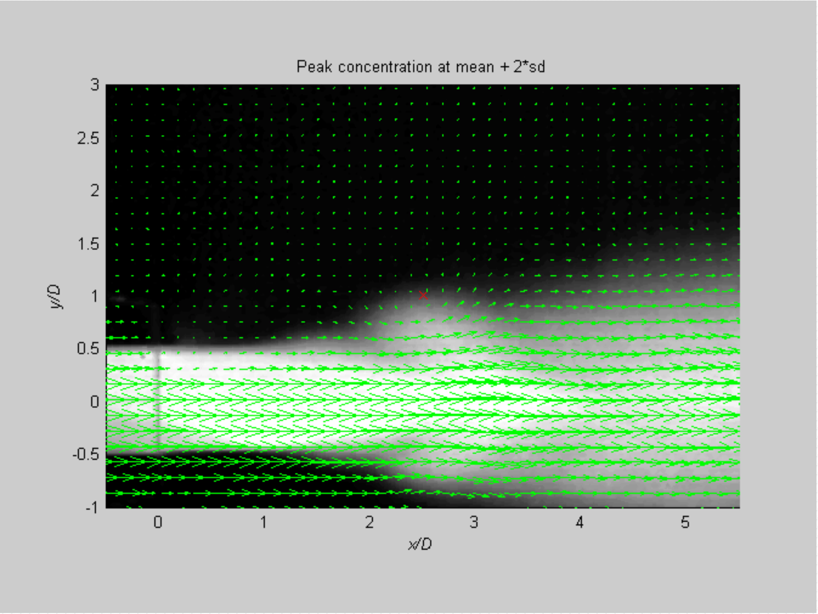
# Conditional Sampling of Concentration

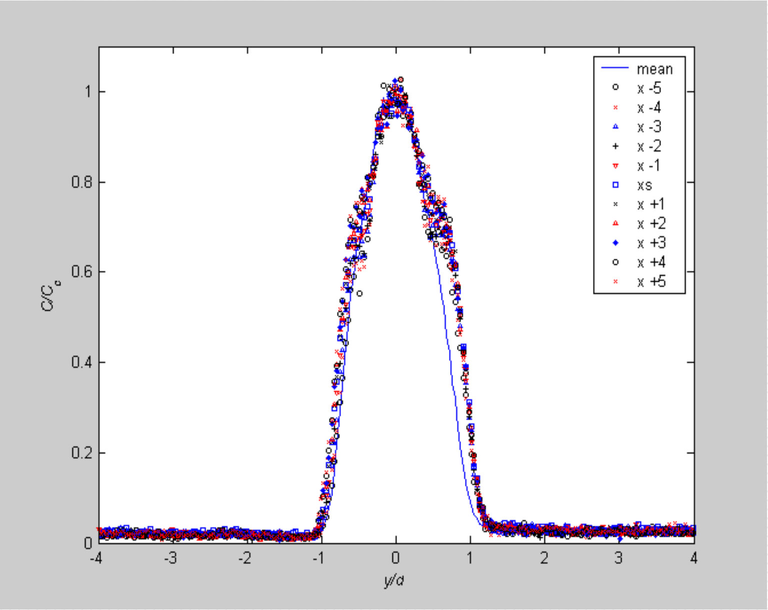
- Select an observation point $P$ $(x_p, y_p)$ at the estimated boundary;
- Use an investigation window to obtain the mean concentration $C_{mean}$ inside the window ($0.05D$ x $0.1D$)

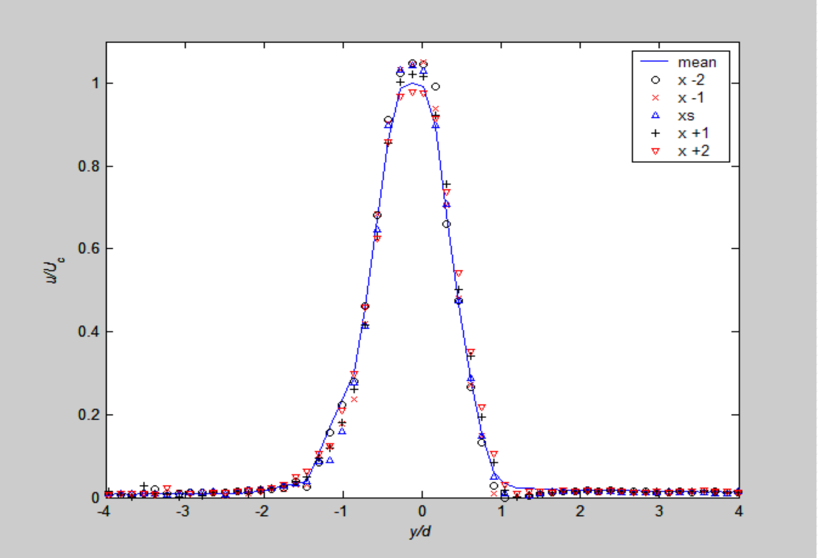


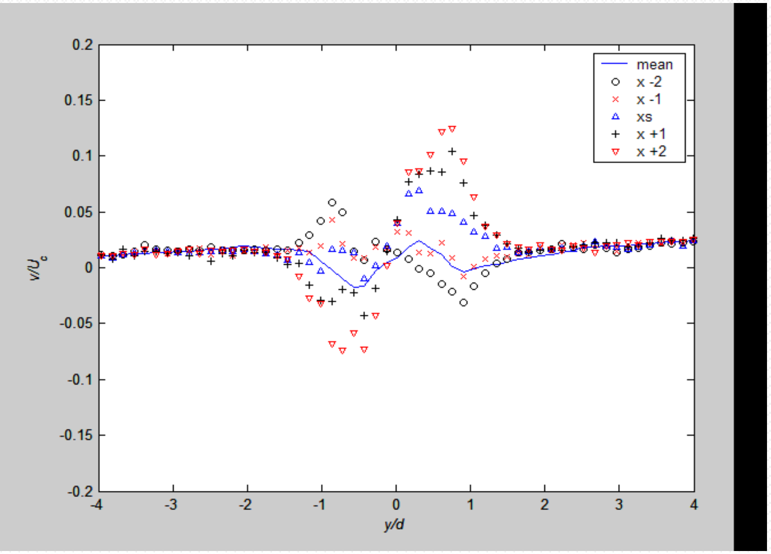

- Set a Peak Factor, g, such that in the sampled instantaneous concentration field: $C_{mean} > C_{p\_avg} + g{\cdot}\sigma_P$ ($g$>0), or $C_{mean} < C_{p\_avg} + g{\cdot}\sigma_P$ ($g$<0), where $C_{p\_avg}$ and $\sigma_P$ are the time-averaged concentration at $P$ and its standard deviation, respectively. ($g$=2)
- Average the conditionally sampled concentration fields and their corresponding velocity fields.

# Observation point at (2.5D, 1D)

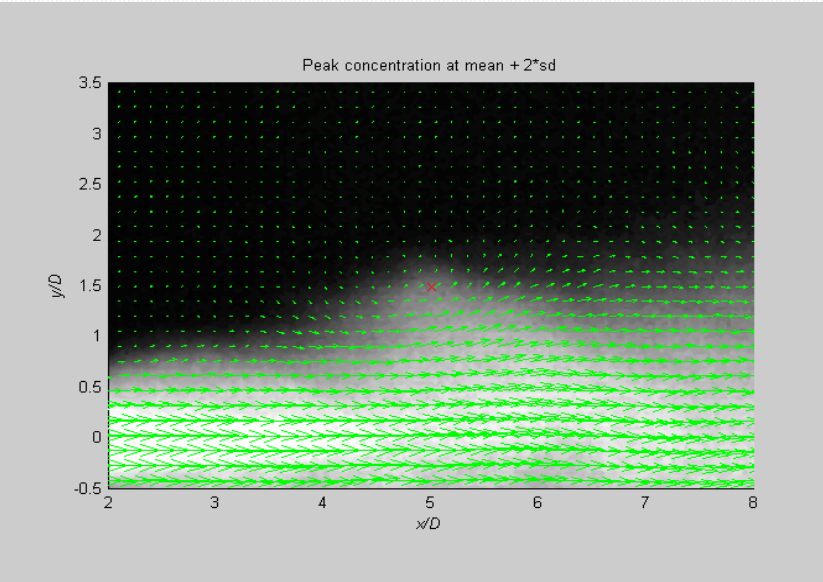


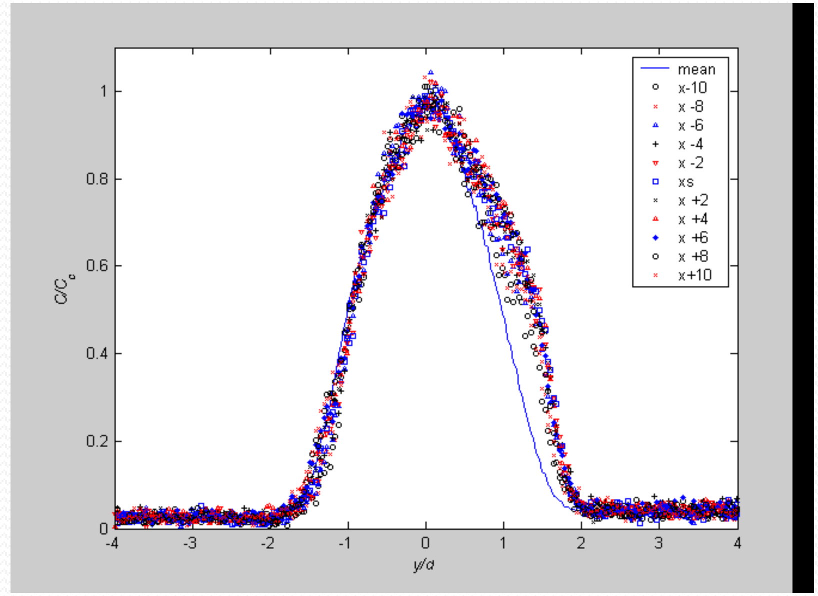



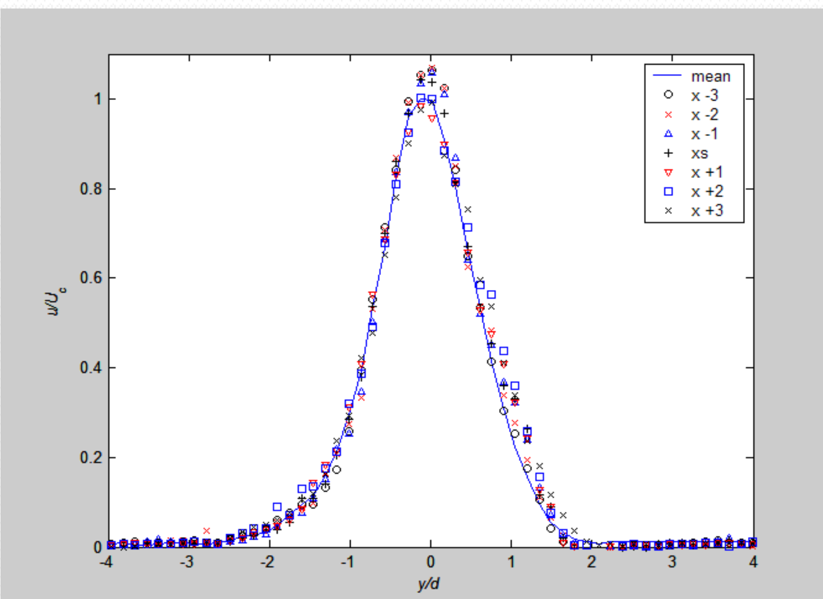



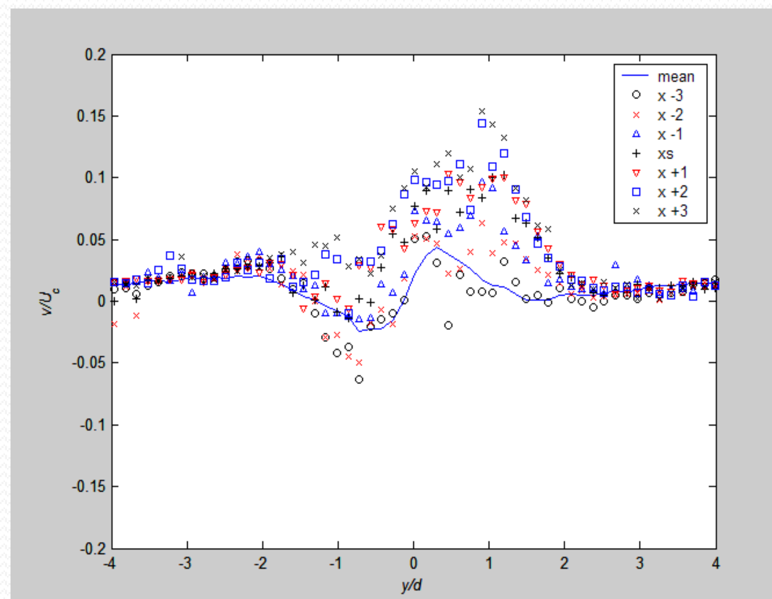



# Observation point at (5D, 1.5D)

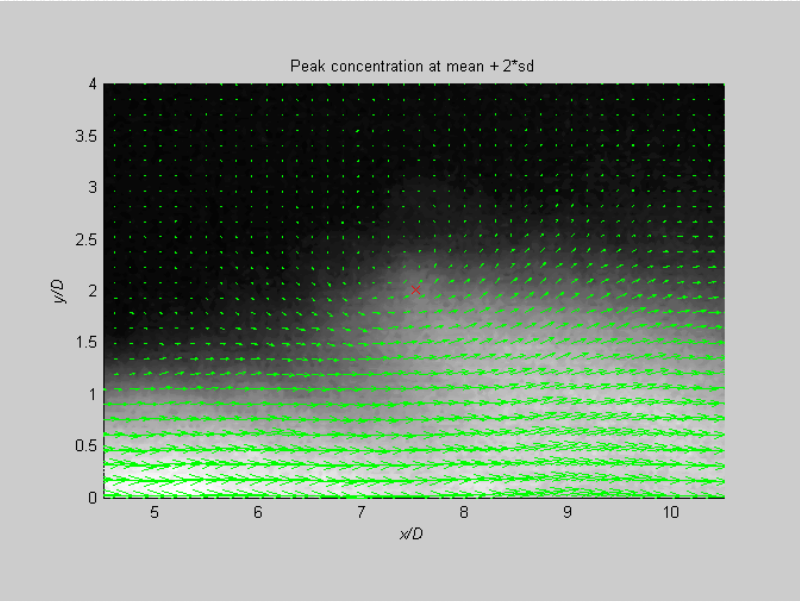


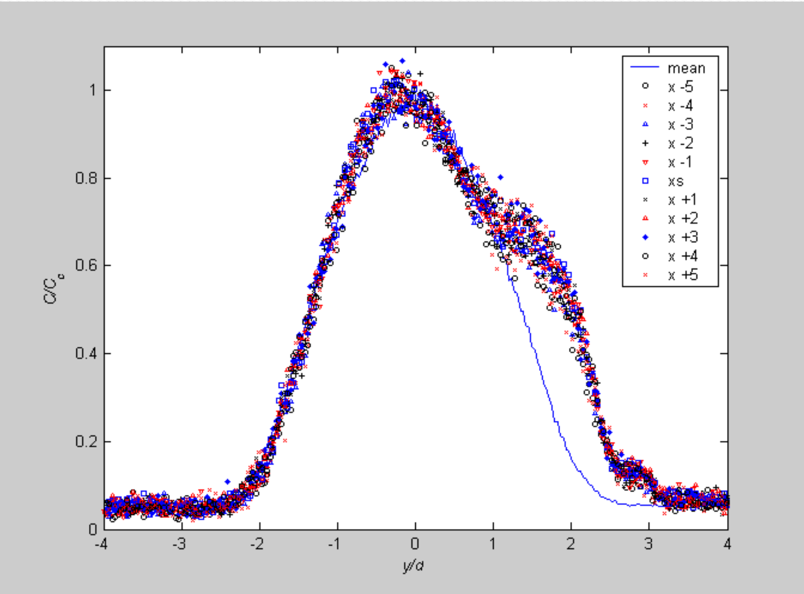



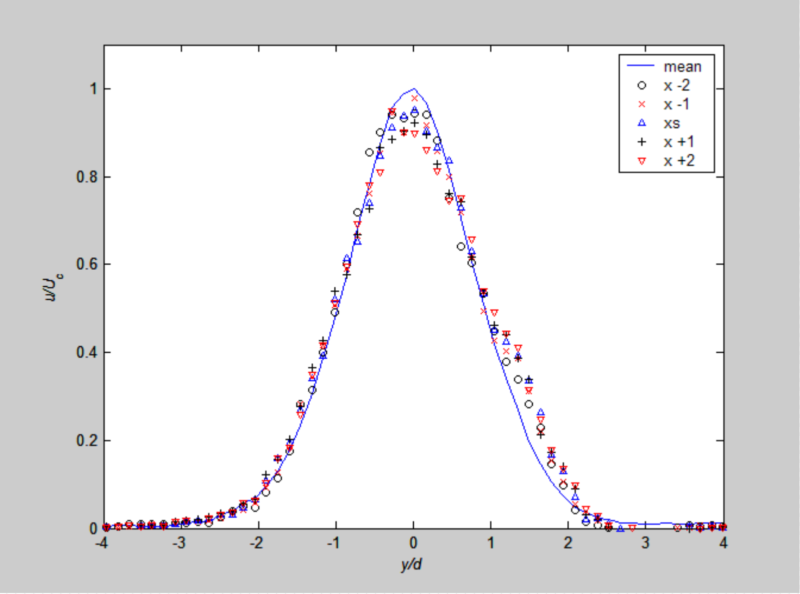



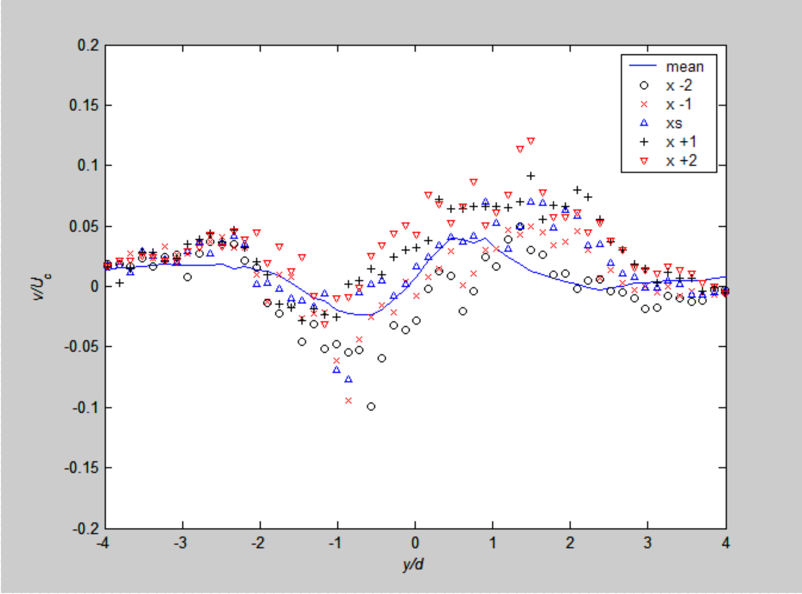



# Observation point at (7.5D, 2D)



# Conclusions

- Rectangular jets with AR≥10 have half power law decay after 4-5D , and can be considered as quasi-2D in this region;
- It is verified that within the quasi-2D zone, rectangular jet concentration spreads 34% faster than the velocity;
- In the region nearby the exit (2-2.5*D*) there is symmetric vortex effect on velocity and concentration fluctuations, namely along both +y and -y axis high concentration is found to be associated with large radial velocity fluctuations *v*';
- After 2.5D, the copresence of large +*c*' and +*v*' fluctuations is non-axisymmetric, i.e. only appears on one side of y axis.

# Thank you!