Water Flume Measurements of Buoyant Plume Rise and Dispersion from Multiple Stacks

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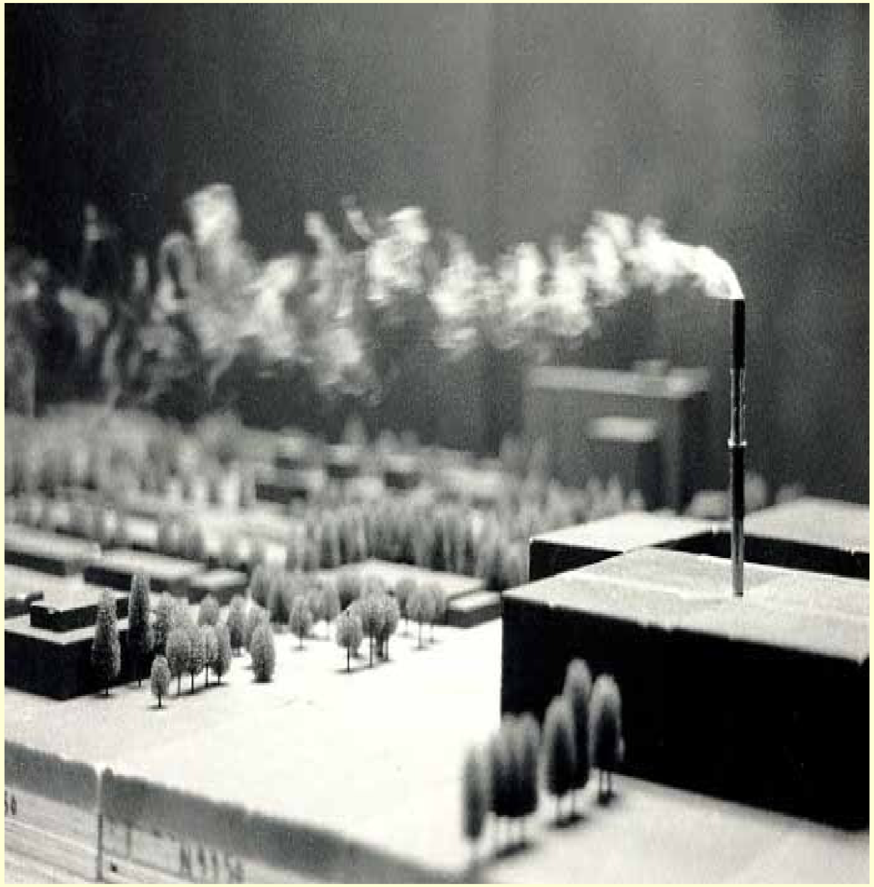
Outline

- Background and Motivation
- Introduction
- Experimental Setup and Technique
- Experimental Procedure
- Data Analysis Procedure
- Results and Discussion
- Conclusions and Further Work

Background and Motivation

1. Previous research: single exhaust sources only.
2. Industrial reality: multiple stacks to discharge the effluent into the atmosphere.
3. In main design guidelines, also only single sources are considered in any detail. [e.g. ASHRAE HANDBOOK]
4. Little physical basis has been confirmed by existing data to support suggestions given for multiple stacks.
5. Experiments where geometrical and fluid mechanics aspects of stack dispersion are examined for a range of practical cases are necessary.
6. Purpose: to establish a sound engineering design basis for assessing the exhaust behaviour of clusters of stacks.

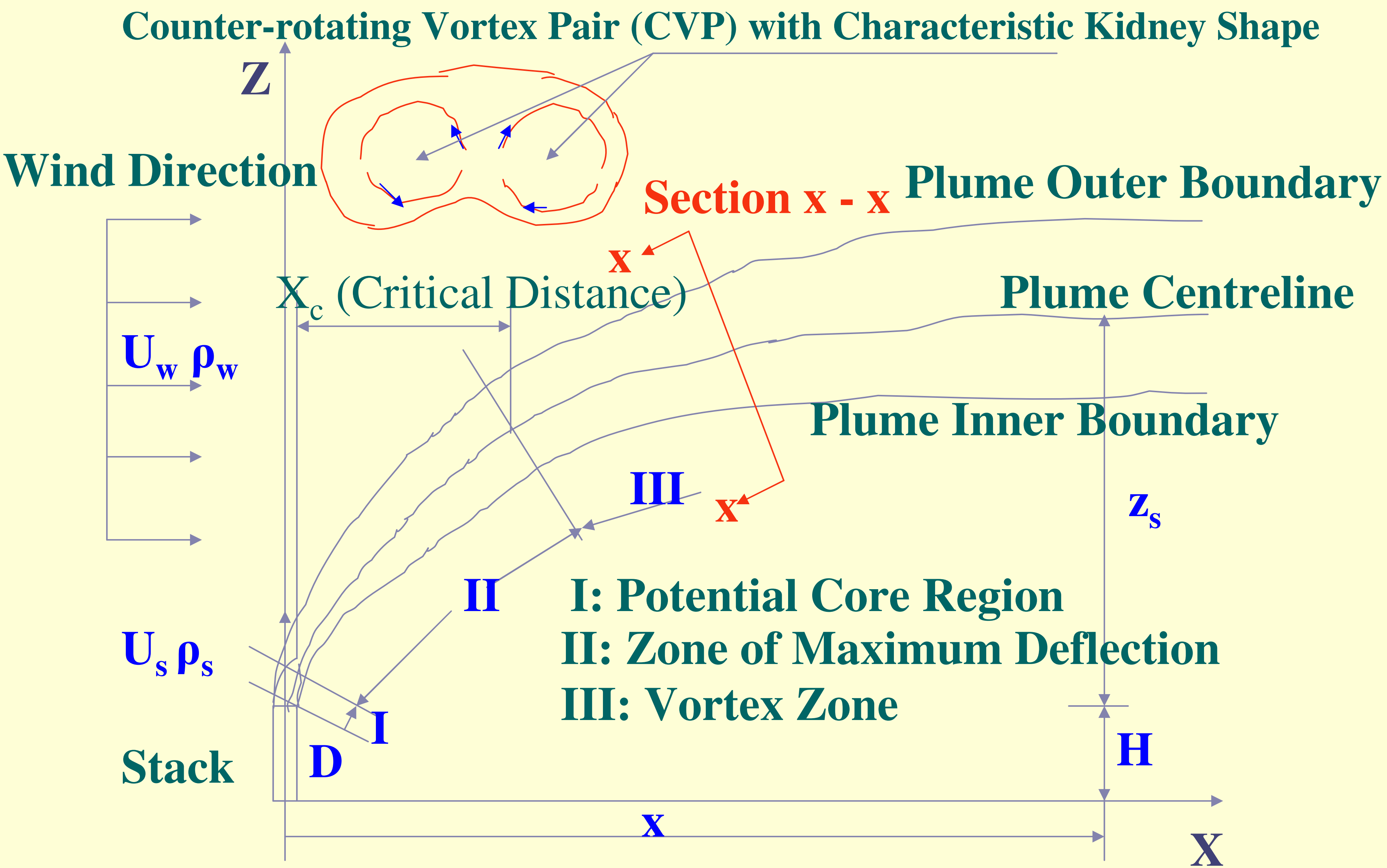
Examples



Much experimental research has been carried out on dispersion from single stacks

However, multiple stacks are commonly used in many industries

Introduction: Definition Sketch of Plume Rise



Key Equations

- **1/3 Power Law for Momentum Jets (Briggs 1984)**

$$\frac{z_s}{l_m} = \left(\frac{3}{\beta_m^2}\right)^{1/3}\left(\frac{x}{l_m}\right)^{1/3} = C_m\left(\frac{x}{l_m}\right)^{1/3}$$

- **2/3 Power Law for Buoyant Plume (Briggs 1984)**

$$\frac{z_s}{l_b} = \left(\frac{3}{2\beta_b^2}\right)^{1/3}\left(\frac{x}{l_b}\right)^{2/3} = C_b\left(\frac{x}{l_b}\right)^{2/3}$$

- **Integral Model for Buoyant Plume (Contini 1999)**

$$z_s = \left[\frac{3F_m x}{\beta_m^2 U_w^2} + \frac{3F_b}{2\beta_b^2 U_w^3}\right]^{\frac{1}{3}}$$

Key Equations

Combined Flux Model (CFM)

$$\frac{z_n}{l_b} = E_n\left(\frac{3}{2\beta_b^2}\right)^{1/3}\left(\frac{x}{l_b}\right)^{2/3} = n^{1/3}\left(\frac{3}{2\beta_b^2}\right)^{1/3}\left(\frac{x}{l_b}\right)^{2/3} = n^{1/3}C_b\left(\frac{x}{l_b}\right)^{2/3}$$

- **Momentum Length Scale**

$$l_m = R_s \frac{Us}{Uw}\sqrt{\frac{\rho_s}{\rho_a}}$$

- **Buoyant Length Scale**

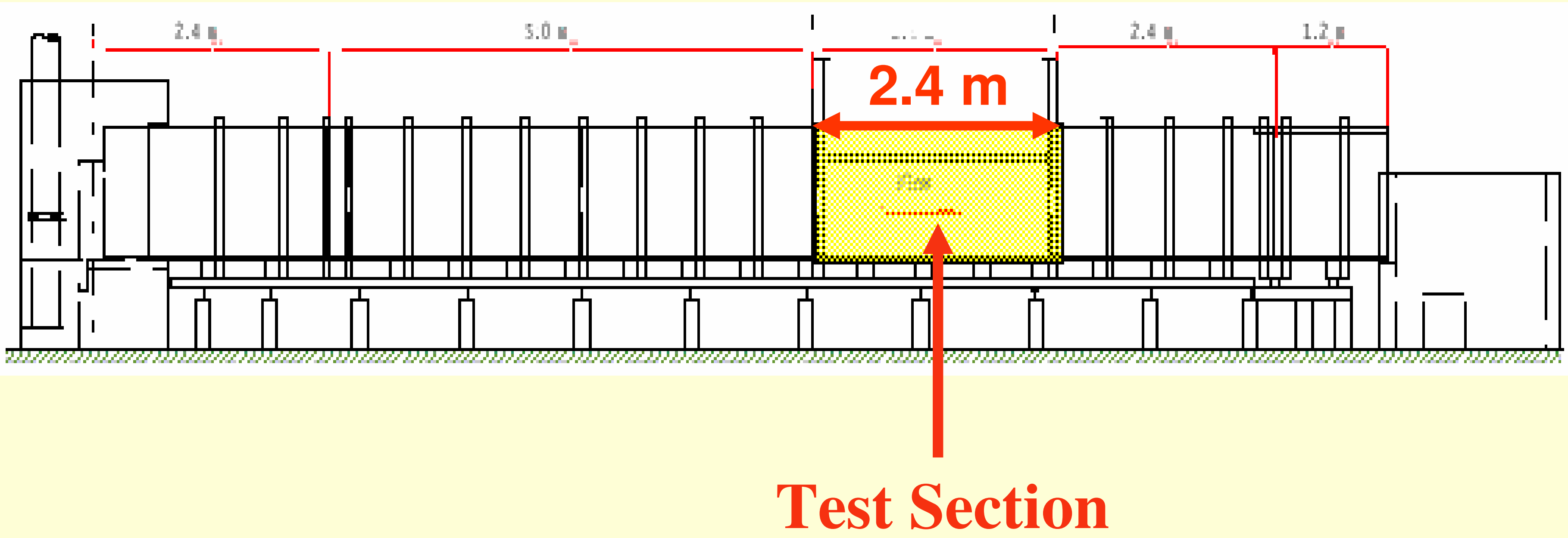
$$l_b = R_s^2 \frac{Us}{Uw^3} g \frac{\Delta\rho}{\rho_a}$$

- **Buoyancy Flux Parameter**

$$F_b = l_b U_w^3$$

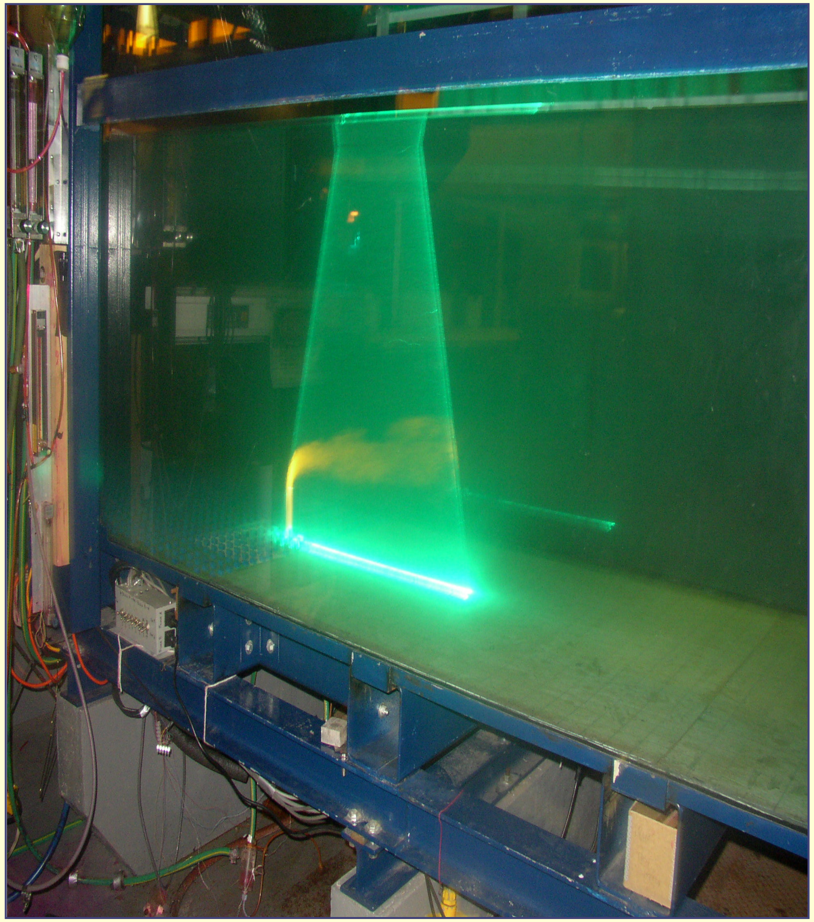
Schematic of the Hydraulic Flume

- Fully developed, turbulent approach flow



- Flume dimensions: 13.4 m x 1.2 m x 1.2 m

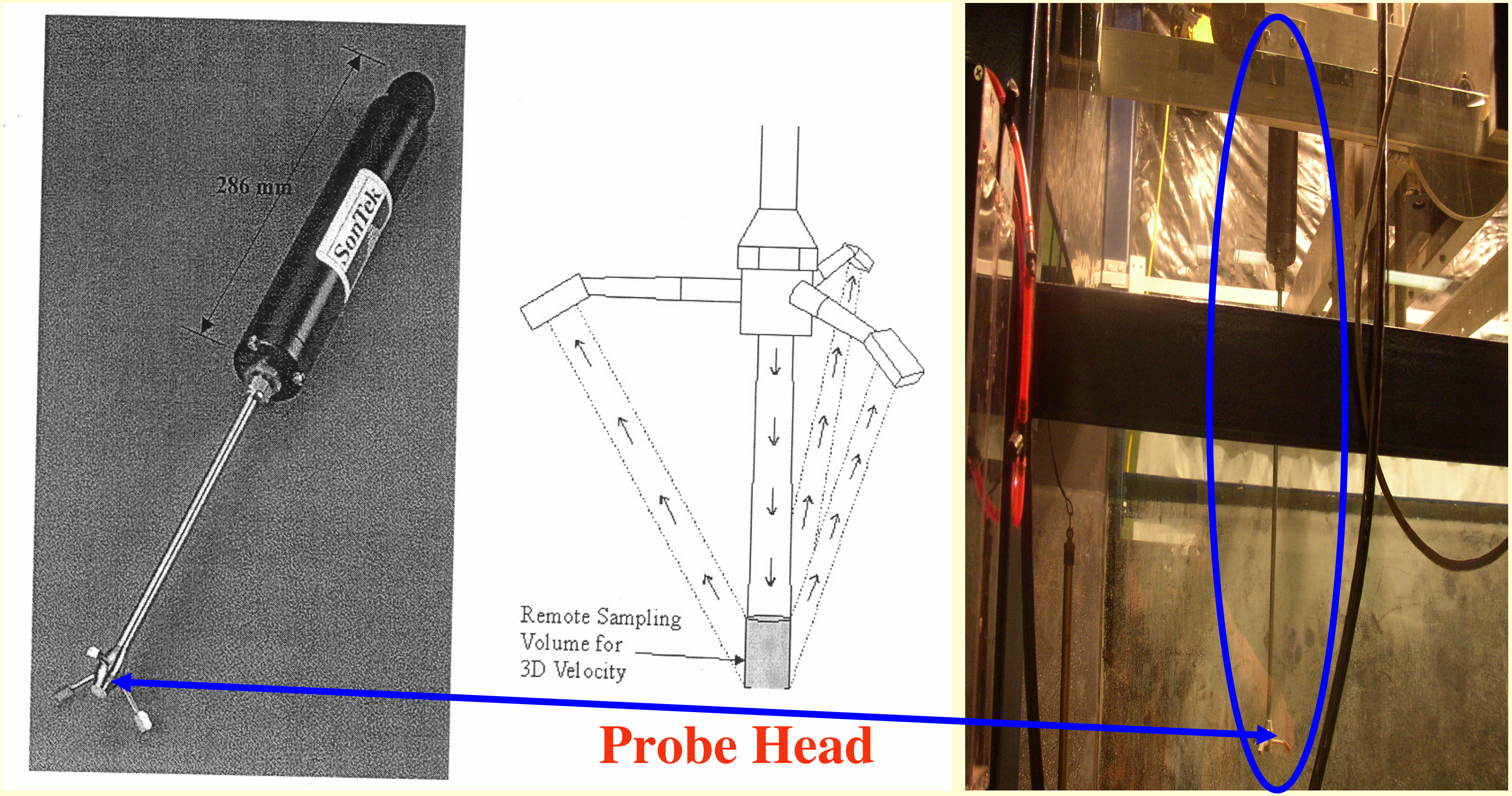
Water Flume



Water flume and laser sheet (Side-View)

Test and flow development sections with model stacks (upstream view)

Micro-Acoustic Doppler Velocimeter

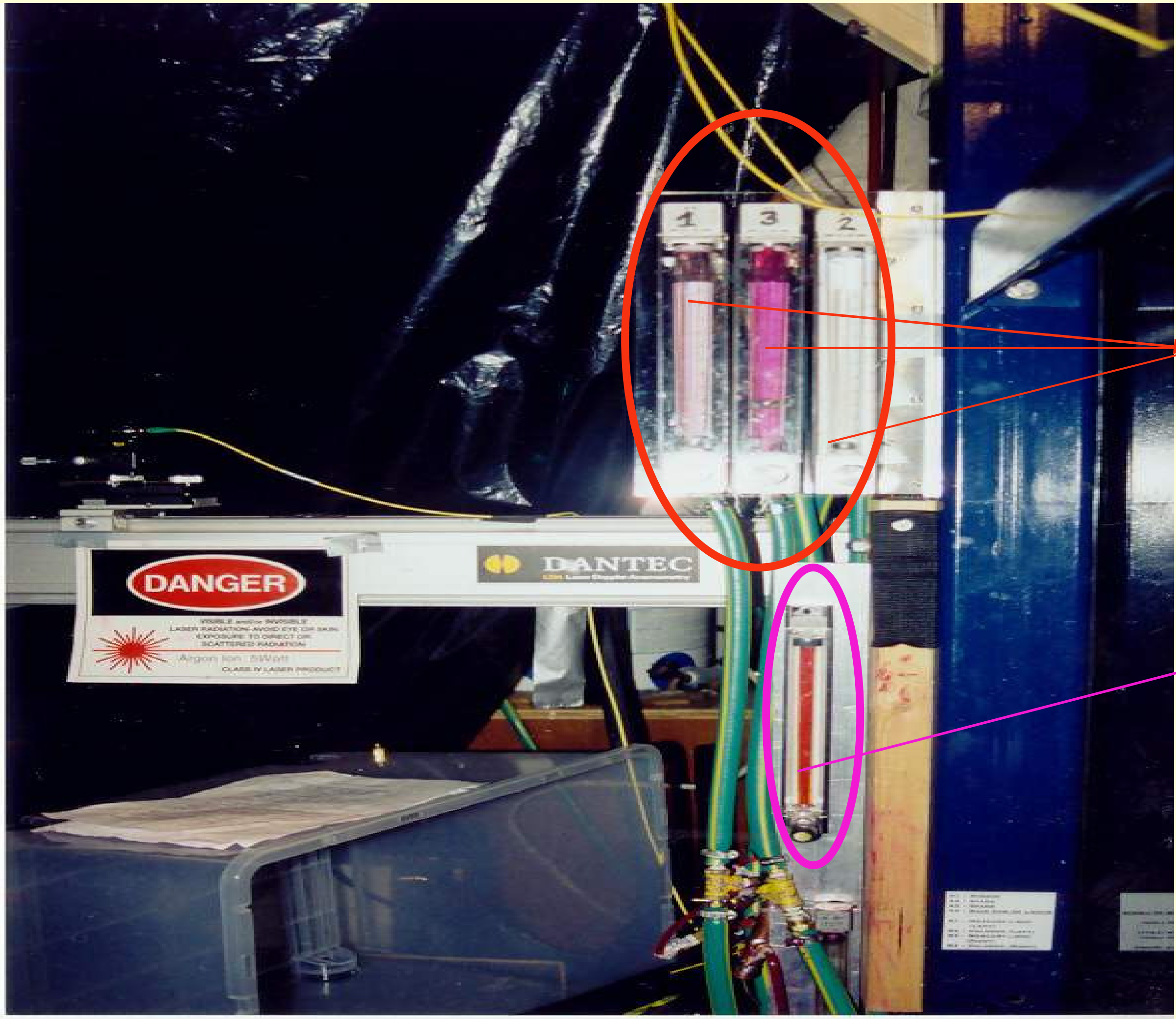


Submersible probe

Schematic of control volume

Experimental setup

Flow Control System

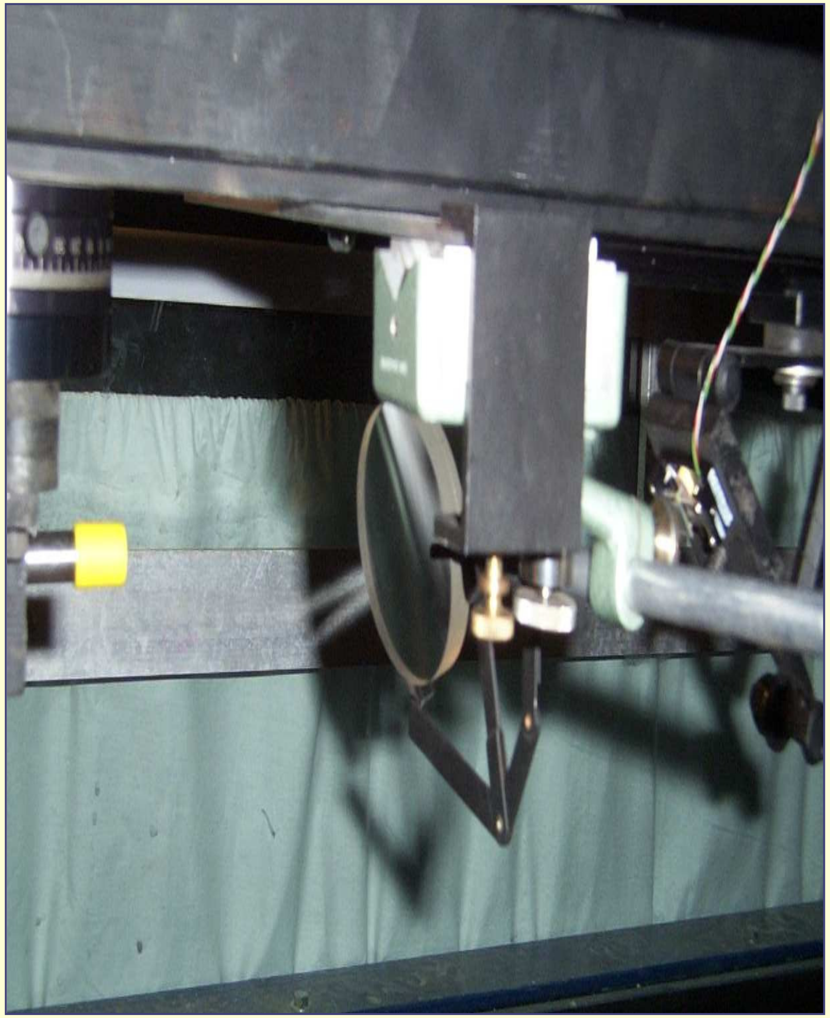


Hot water flow meter

Dye flow meter

Laser System

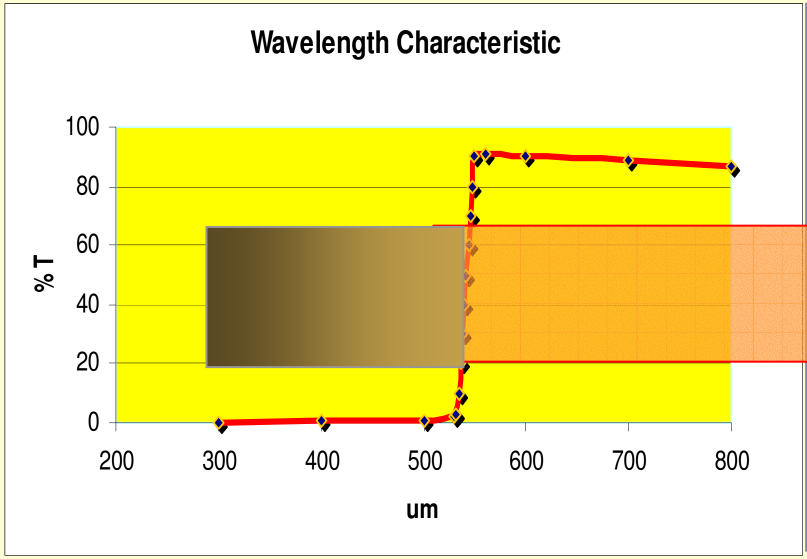
Argon-ion laser

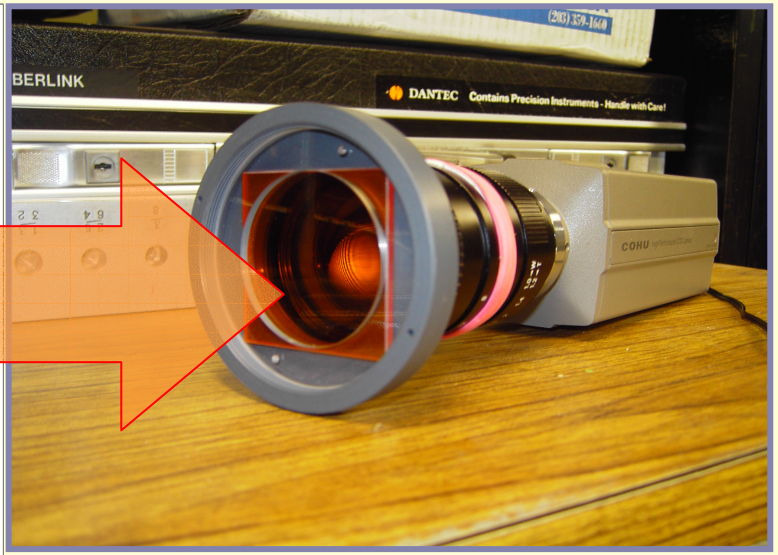


Scanning mirror

Optical Cut-off Filter and Camera

- Only the fluoresced light (555nm) passed to the CCD camera sensor.
- The primary argon-ion laser light (514nm) was blocked.





Video Image Acquisition System

Planar Laser-Induced Fluorescence (PLIF)

•Principle:

Fluorescent dyes absorb excitation light over a range of wavelengths then re-emit light at a longer wavelength.

•Key Points:

1. A suitable laser/dye combination for PLIF measurement (Argon-ion laser + Rhodamine WT).

2. A careful calibration to make sure the intensity of the fluoresced light is proportional to the local intensity of the excitation source and the local concentration of dye.

3. After calibration, the digital images of the instantaneous intensity distribution are converted to the concentration field.

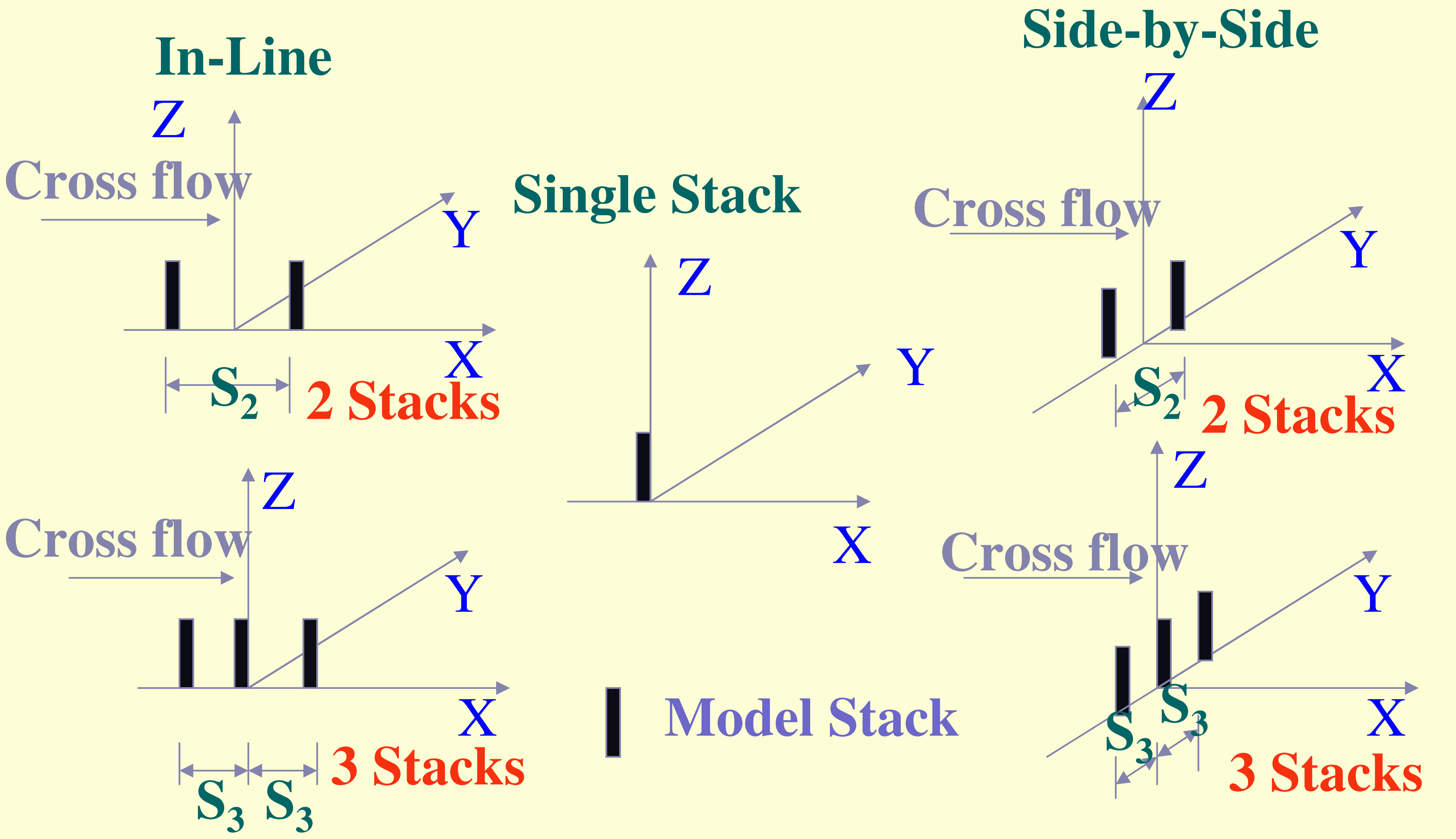
Experimental Procedure

1. Simulated atmospheric boundary layer measurements
2. Calibration measurements
3. Plume cross section concentration field measurements
4. Physical scaling ruler

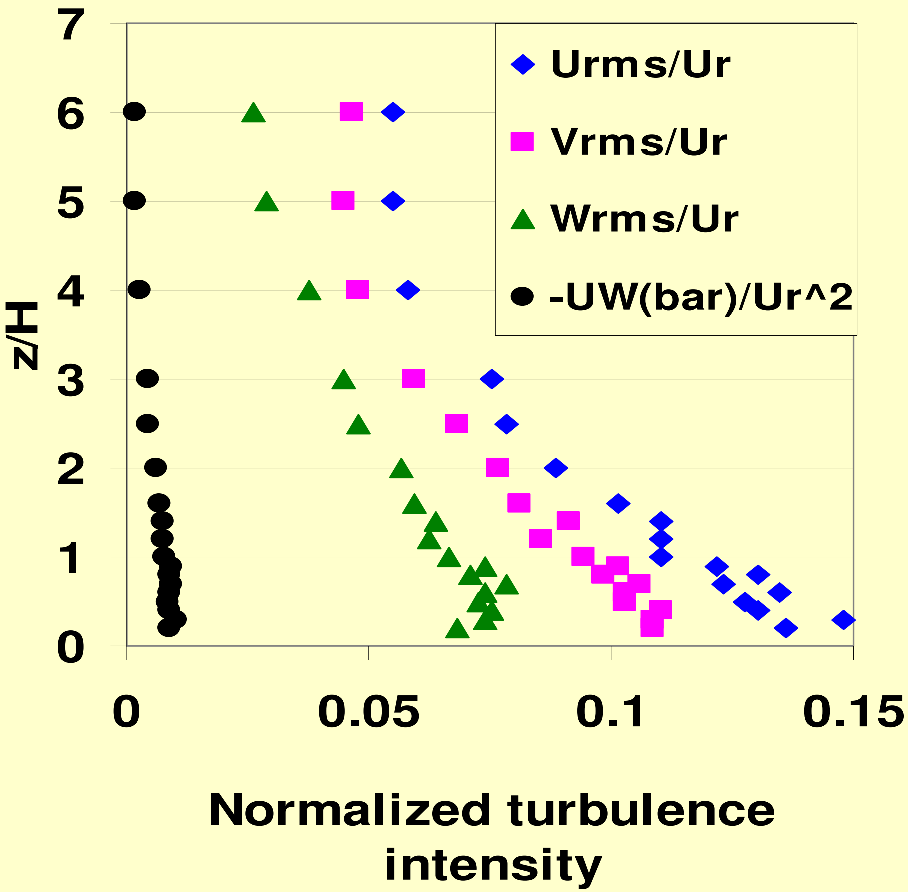
Basic Modeling Parameters

- Model stack inside diameter D=11.5mm; height H=100mm
- Cross flow velocity U_c = 69mm/s; plume exit velocity U_e =138mm/s, corresponding to velocity ratio a = 2
- Froude number square $Fr^2 = \frac{U_r^2 \rho_a}{\Delta \rho g D}$ was kept at 4.1 for all the experiments.
- Modeling Scale: 1:200
- Aerodynamic roughness length z_0 = 1.7mm with the zero plane displacement d set to 1.5mm.

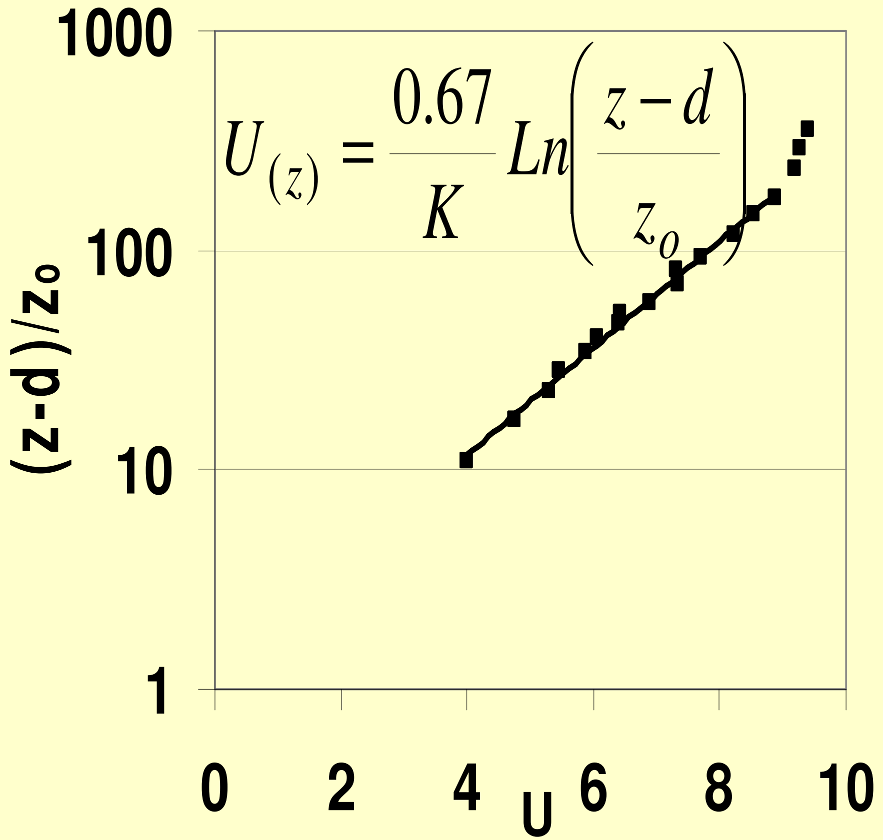
Co-ordinate System and Stack Arrangements



Simulated Atmospheric Boundary Layer

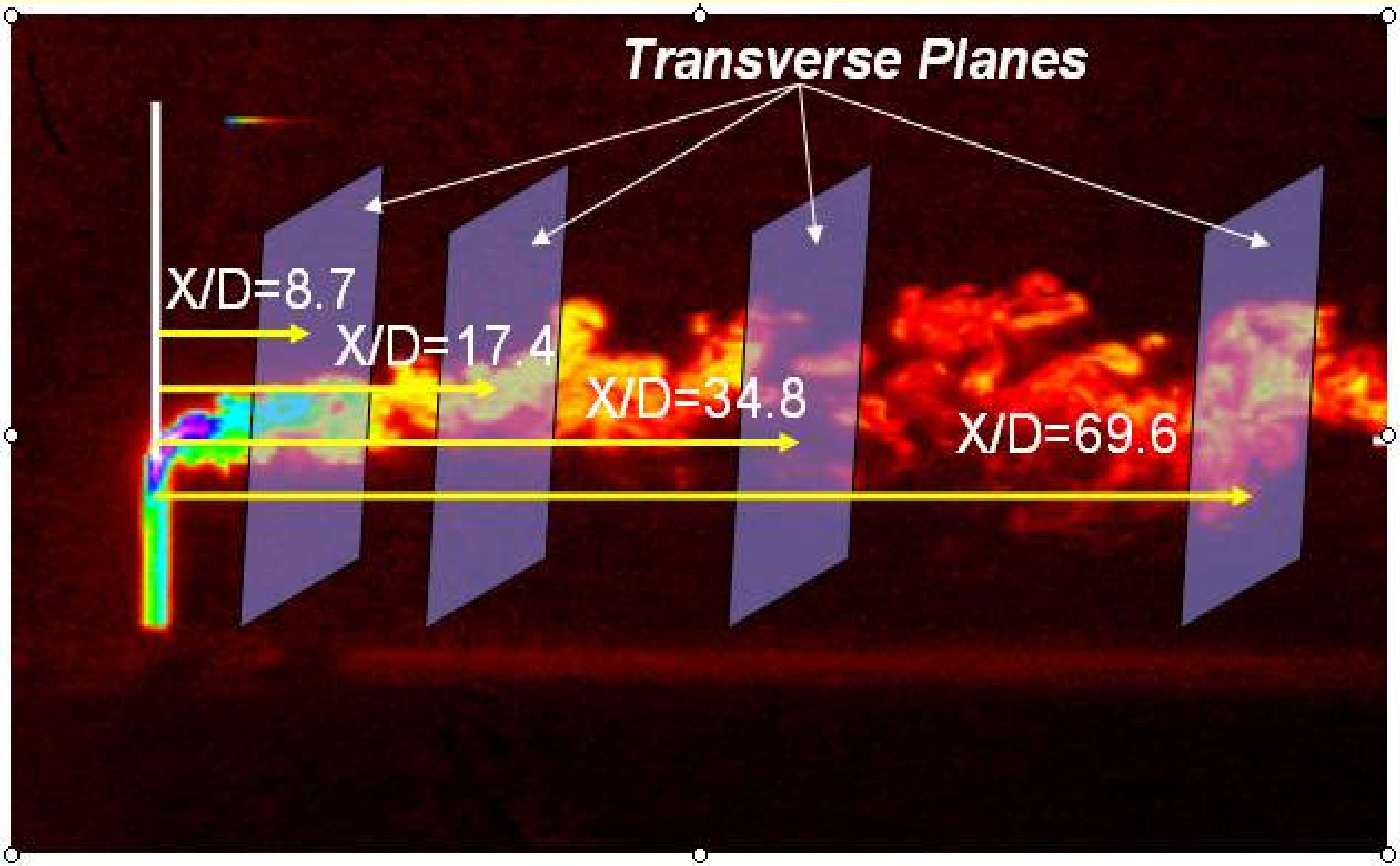


Profiles of normalized turbulence intensity



Semi-log-plot of the mean velocity

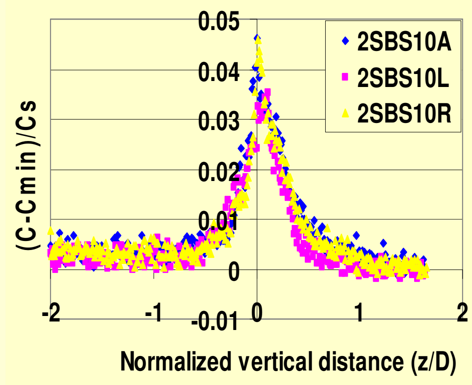
Measurement locations



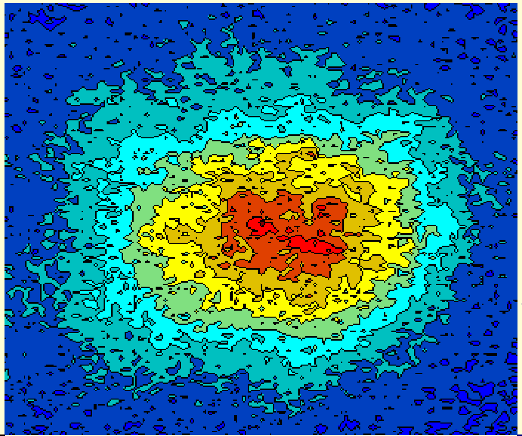
Flow visualization of single stack dispersion

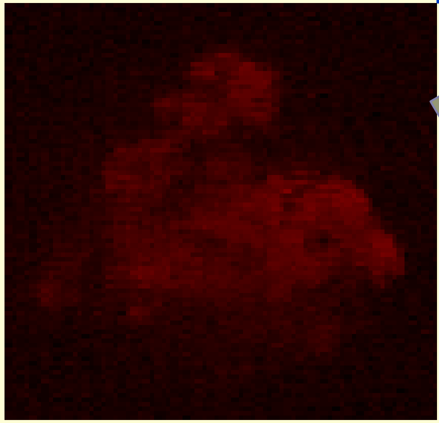
Data Analysis Procedure

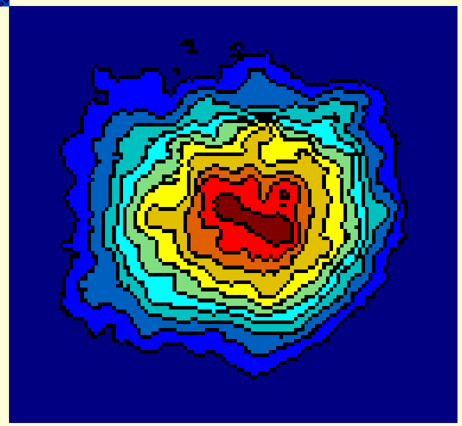
Video images



DigImage

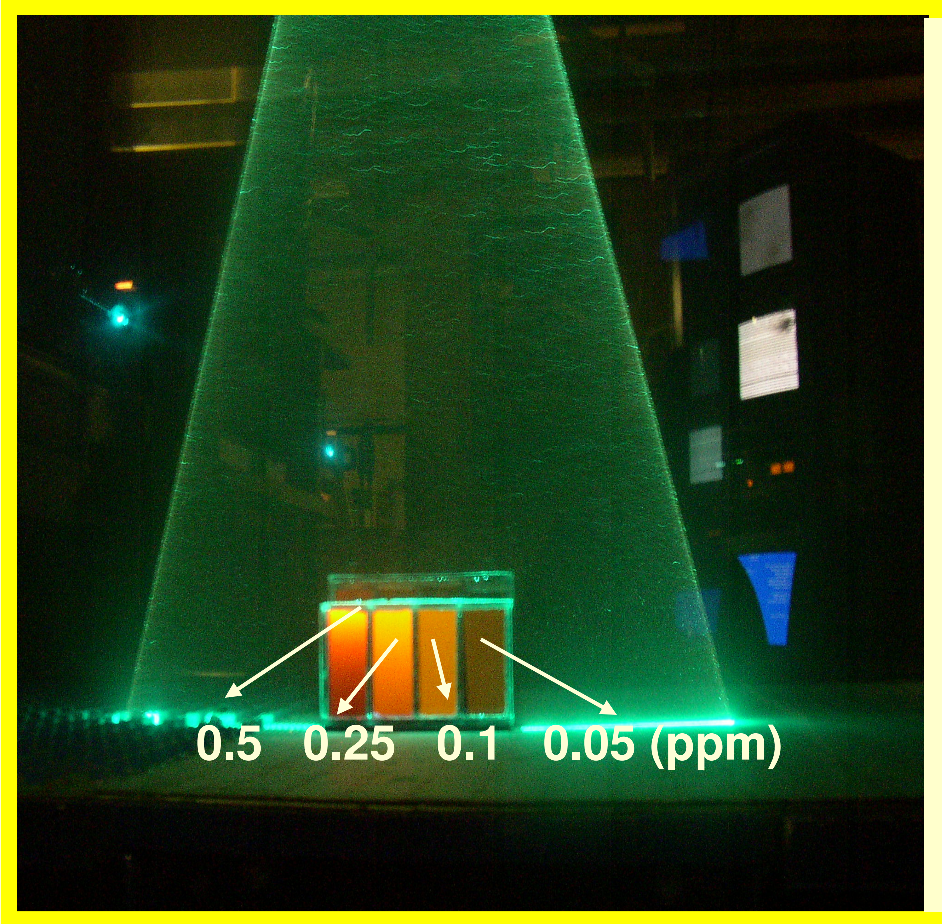




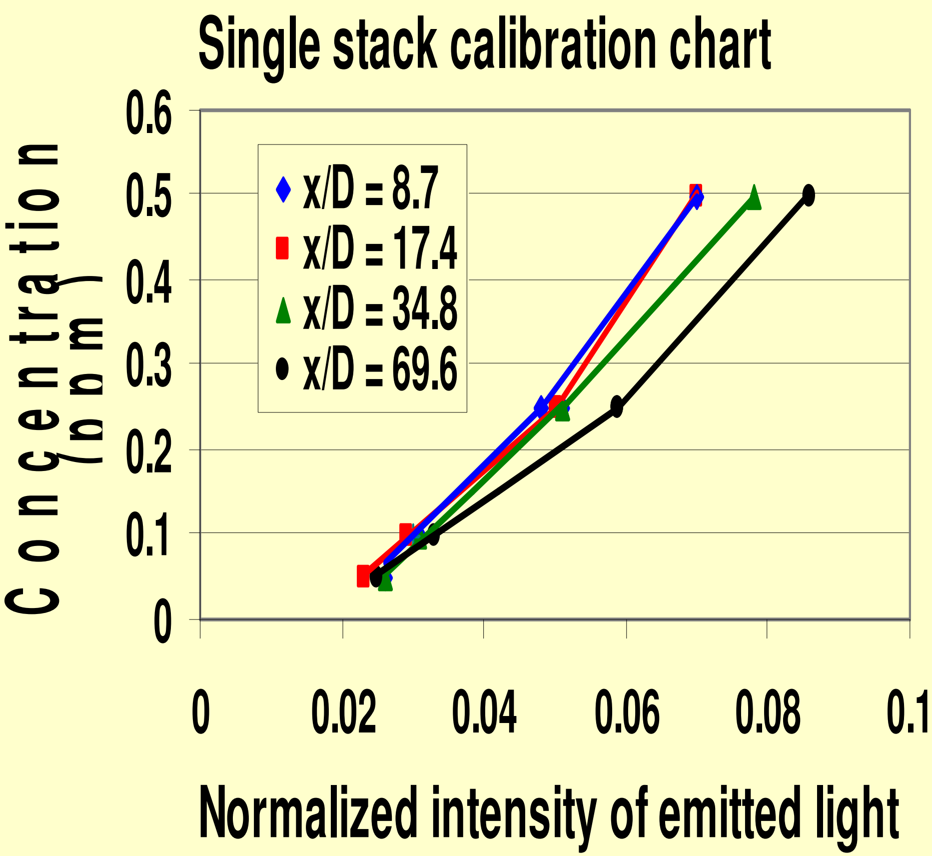


Matlab

PLIF Calibration Measurements

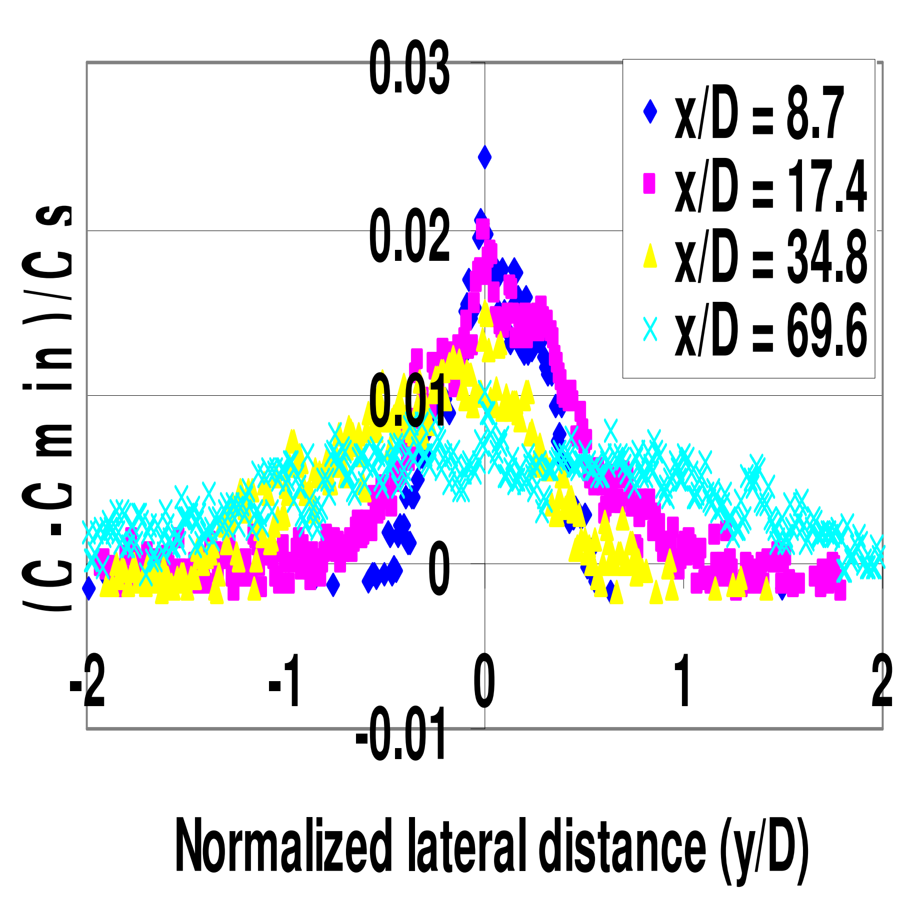


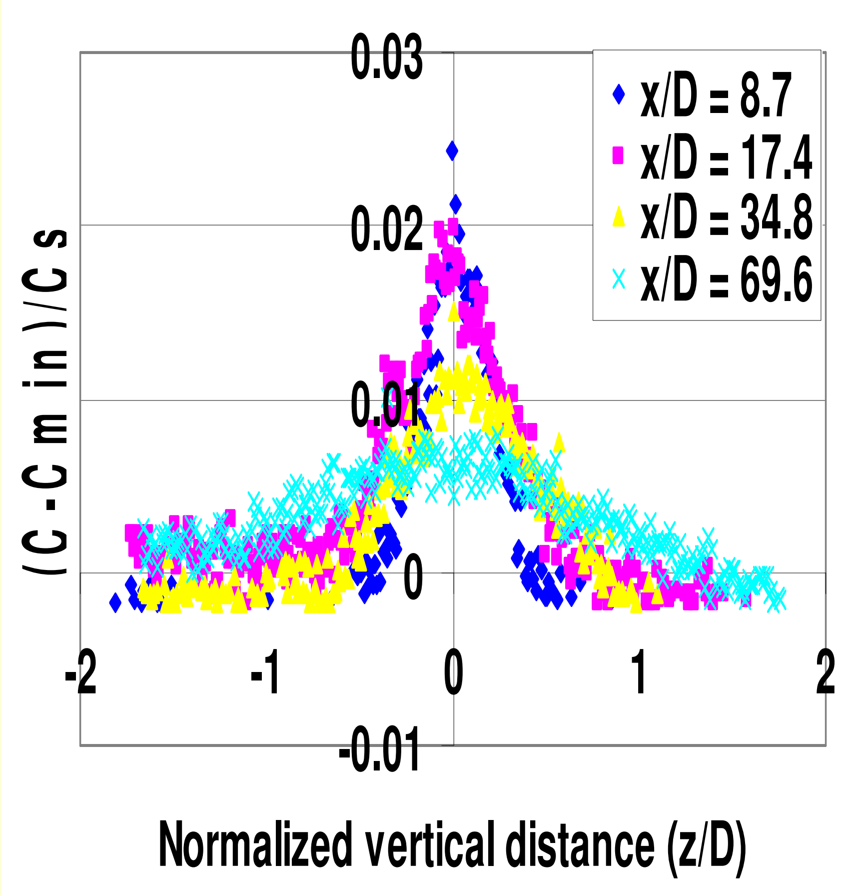
Calibration box measurements



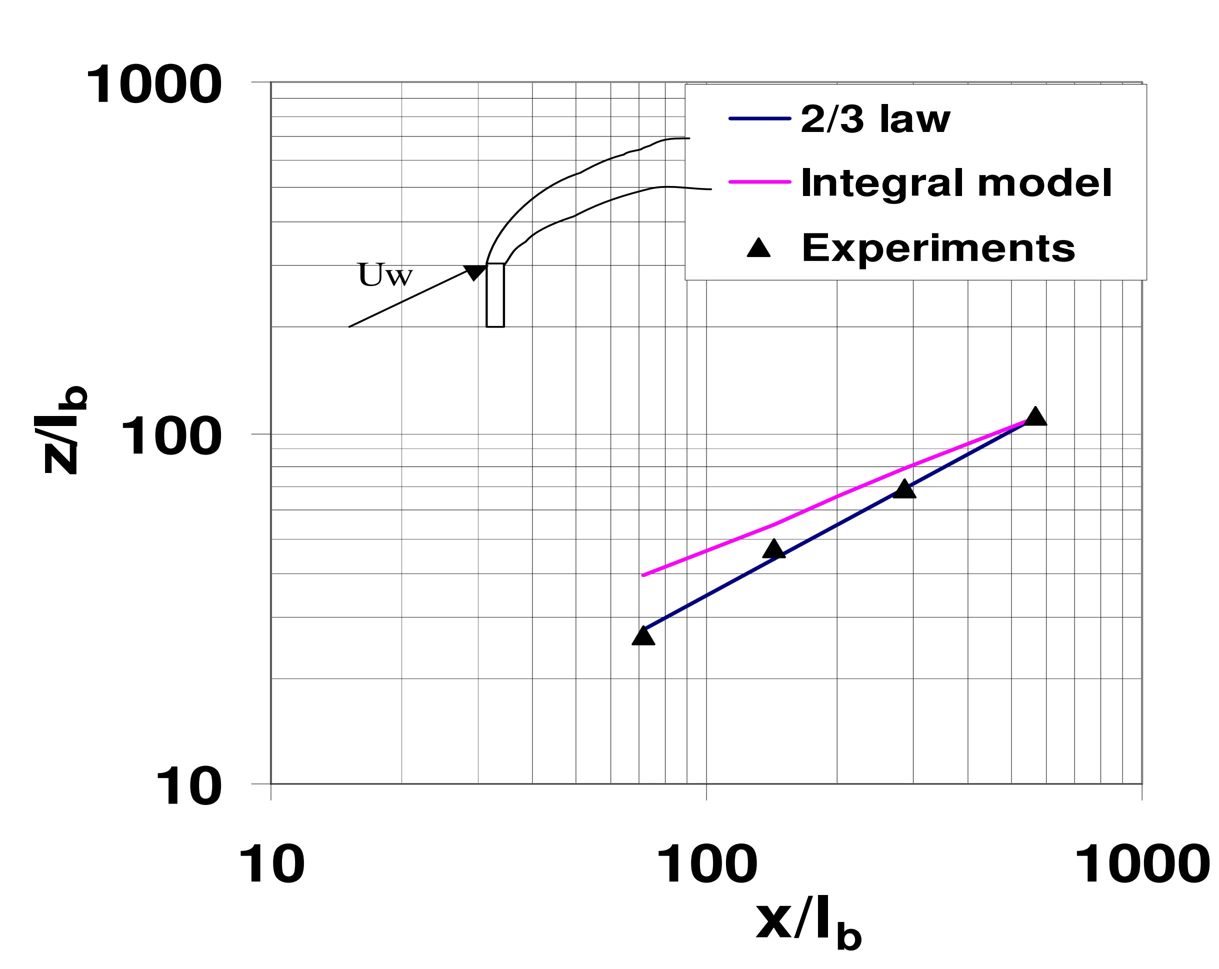
Calibration results

Normalized Gaussian Profiles of Mean Concentration (1S)



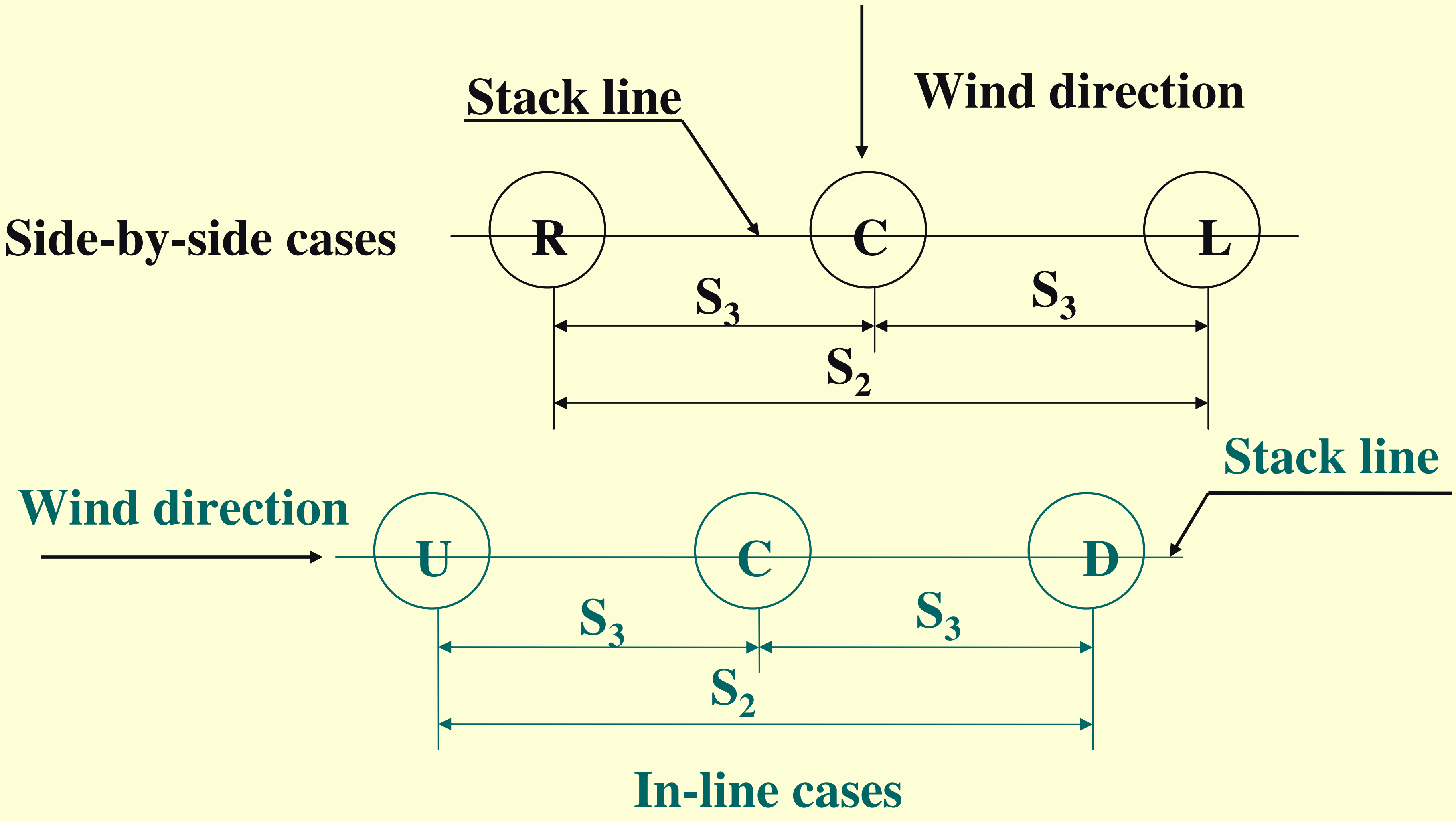


Plume Trajectory Comparison (1S)

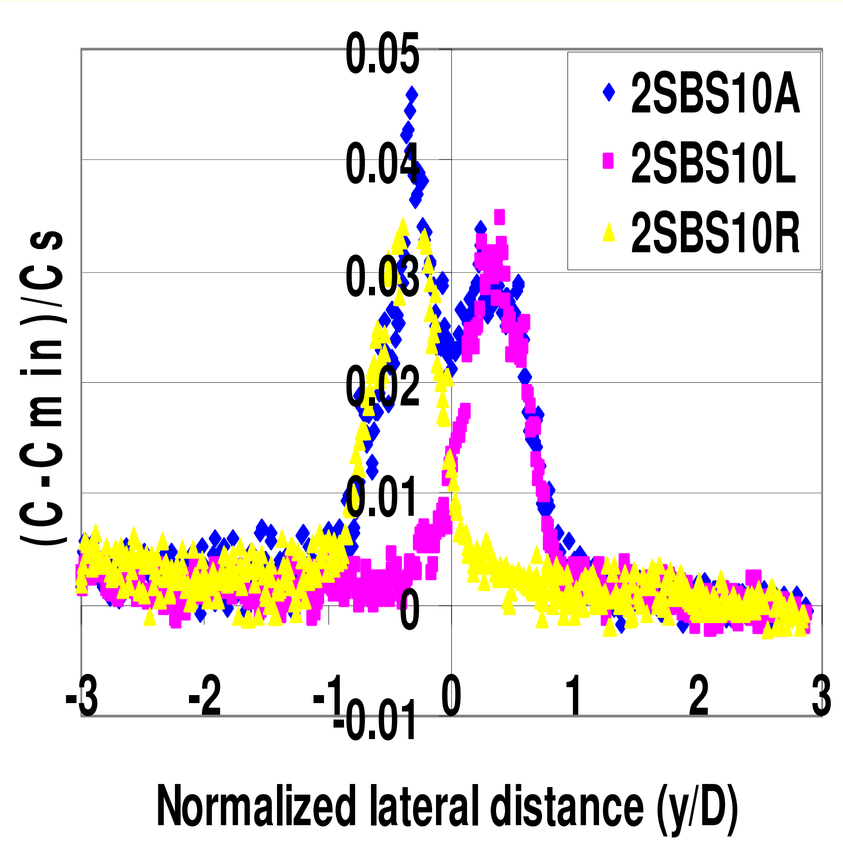


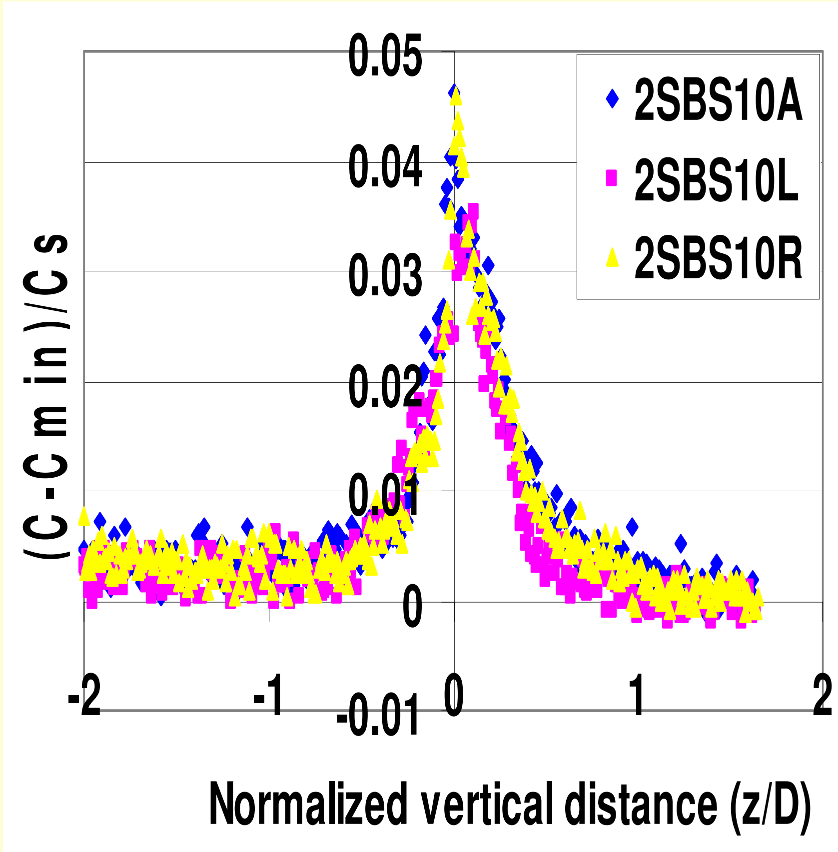
Measured plume trajectory compared with those calculated by the 2/3 law and the integral model

Plume cross-section experimental procedure for multiple stacks



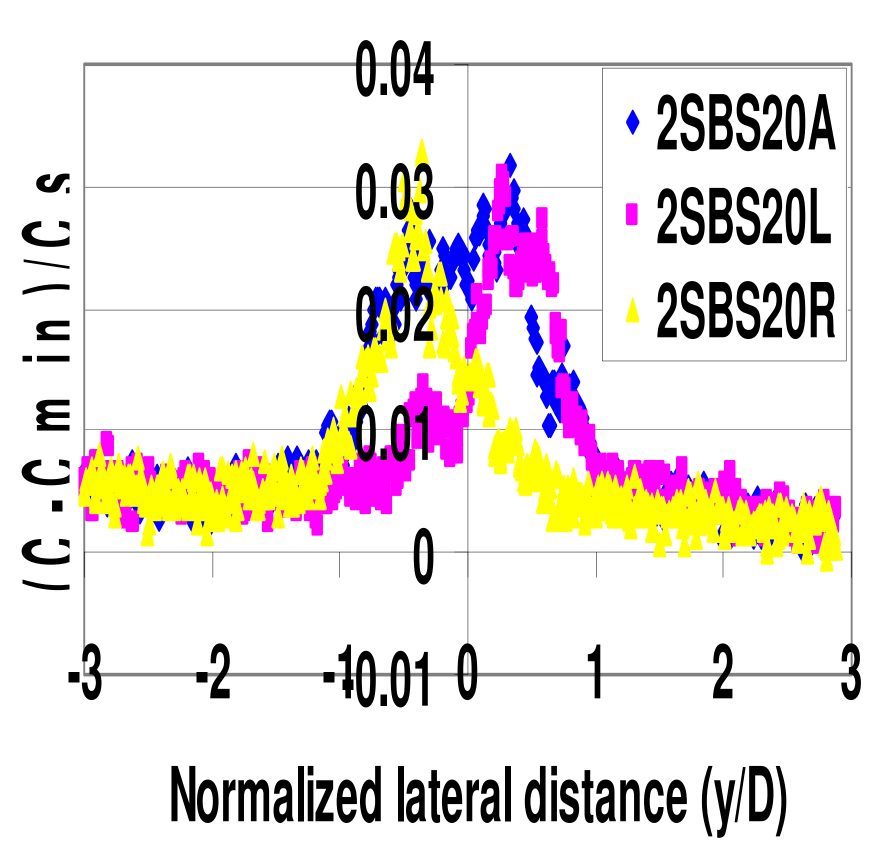
Normalized Gaussian Profiles of Mean Concentration (2SBS)

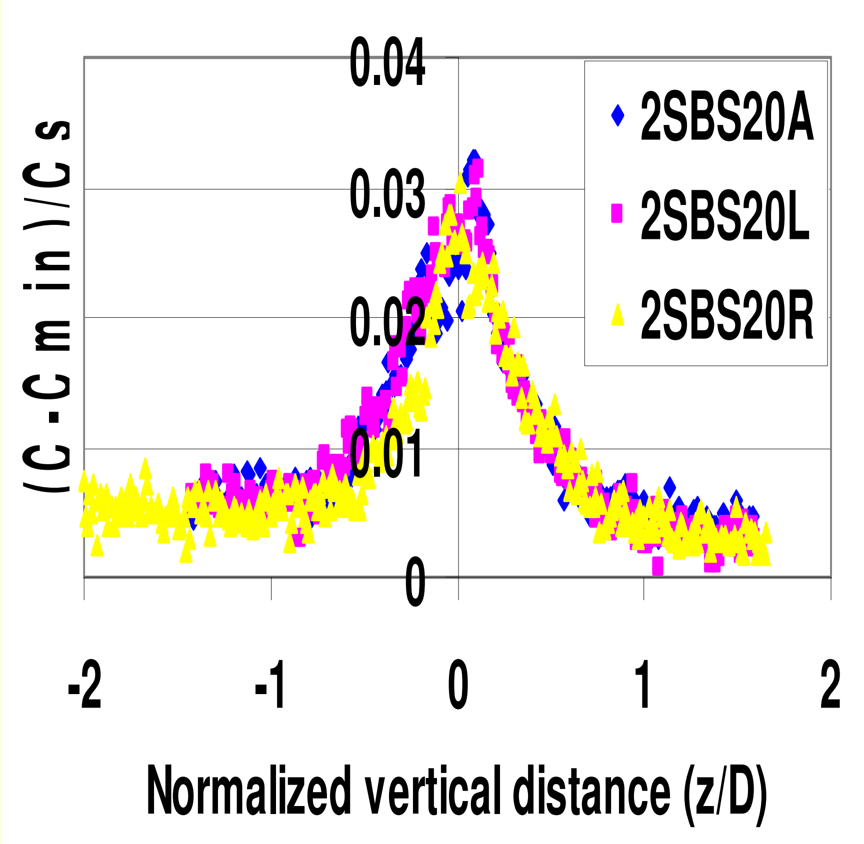




x/D = 8.7

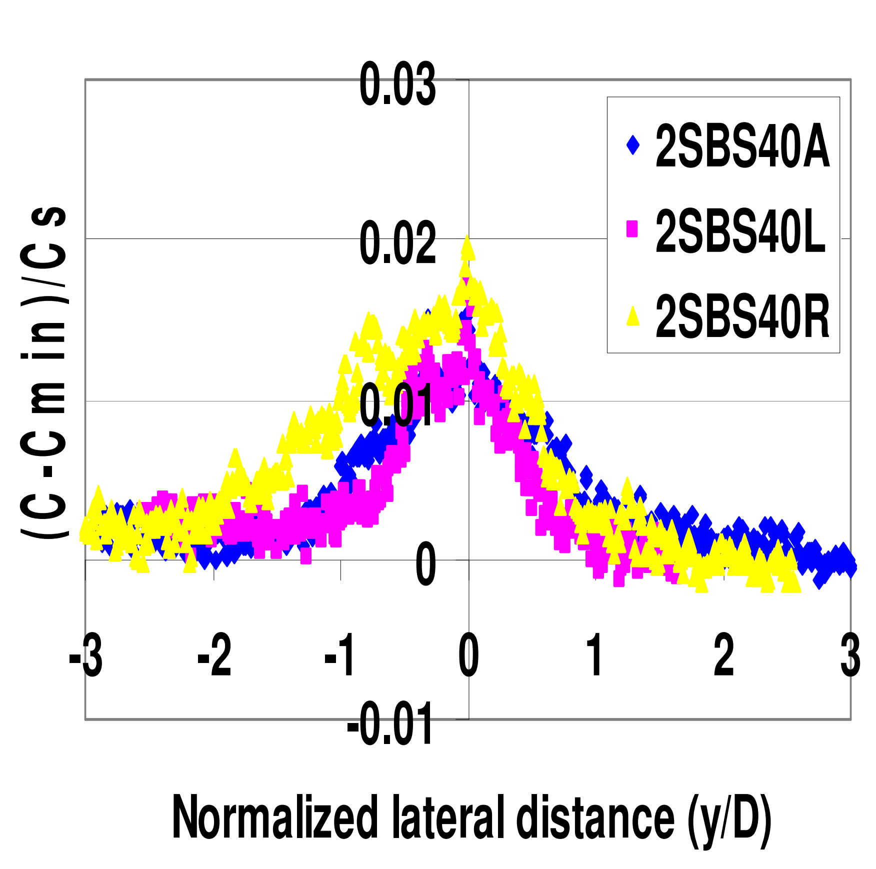
Normalized Gaussian Profiles of Mean Concentration (2SBS)

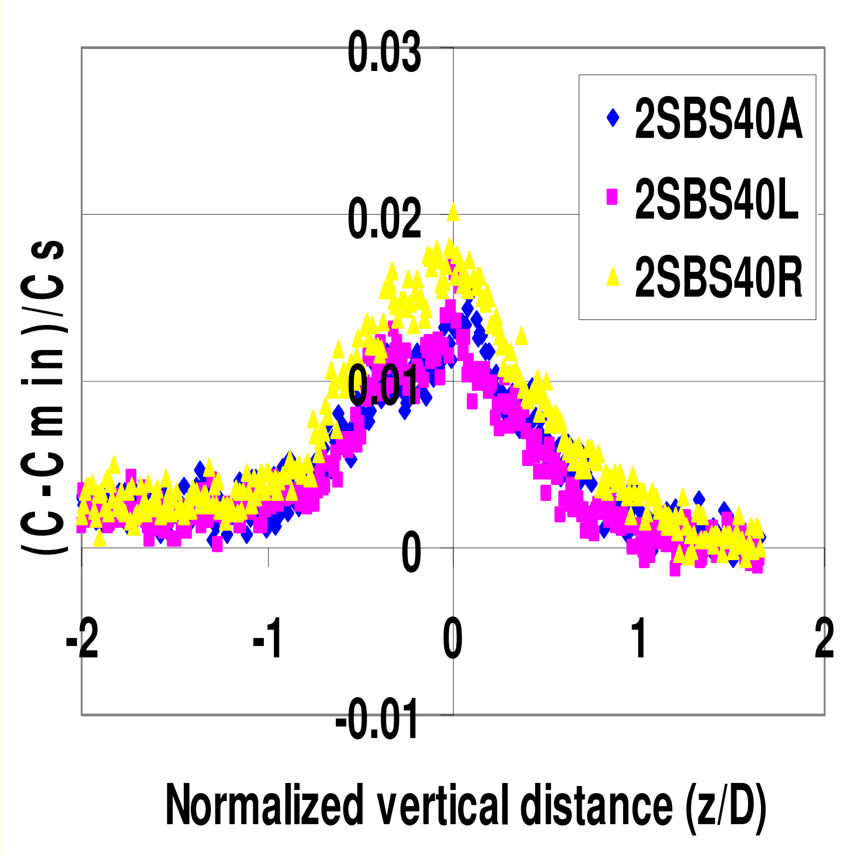




x/D = 17.4

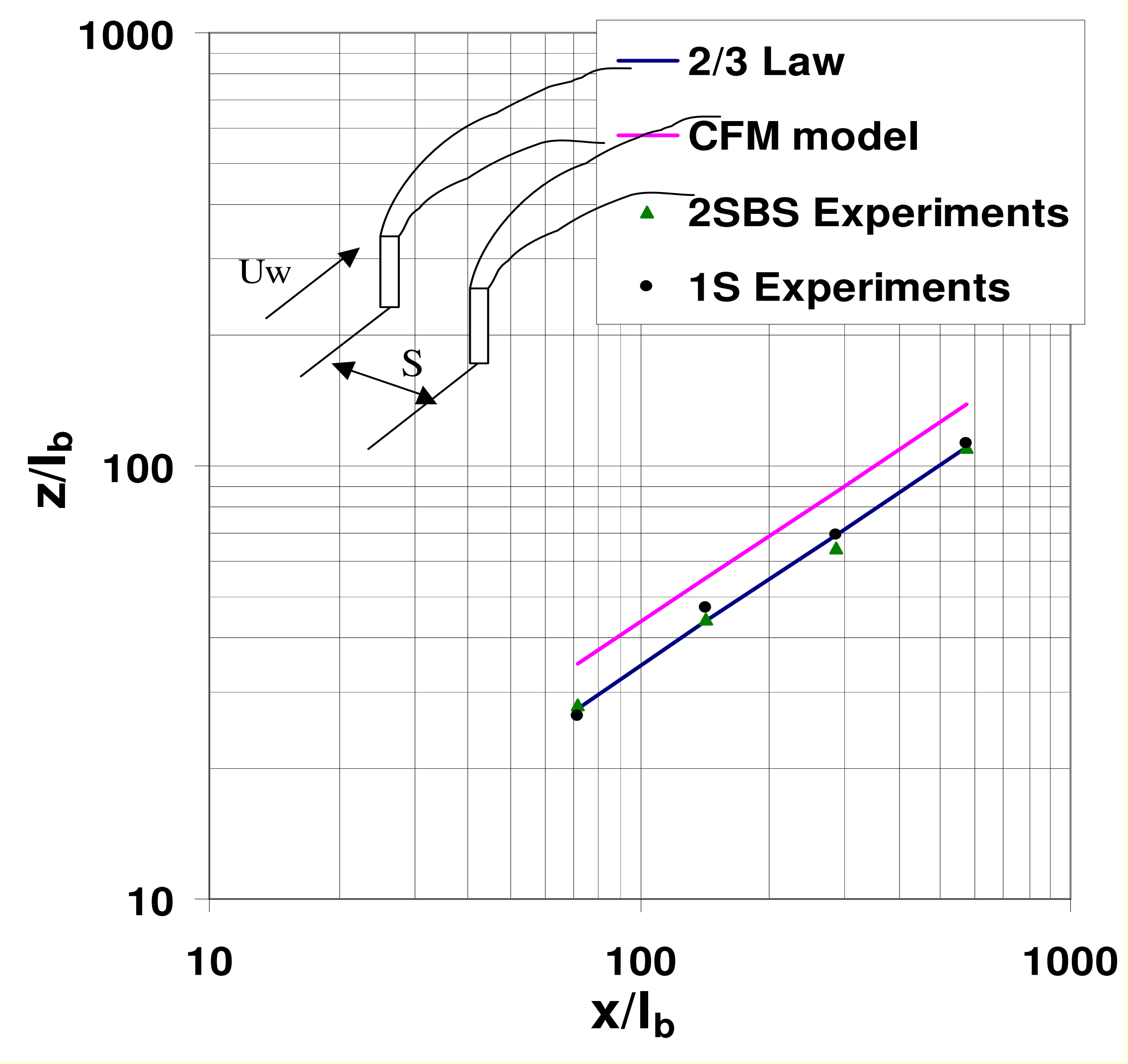
Normalized Gaussian Profiles of Mean Concentration (2SBS)



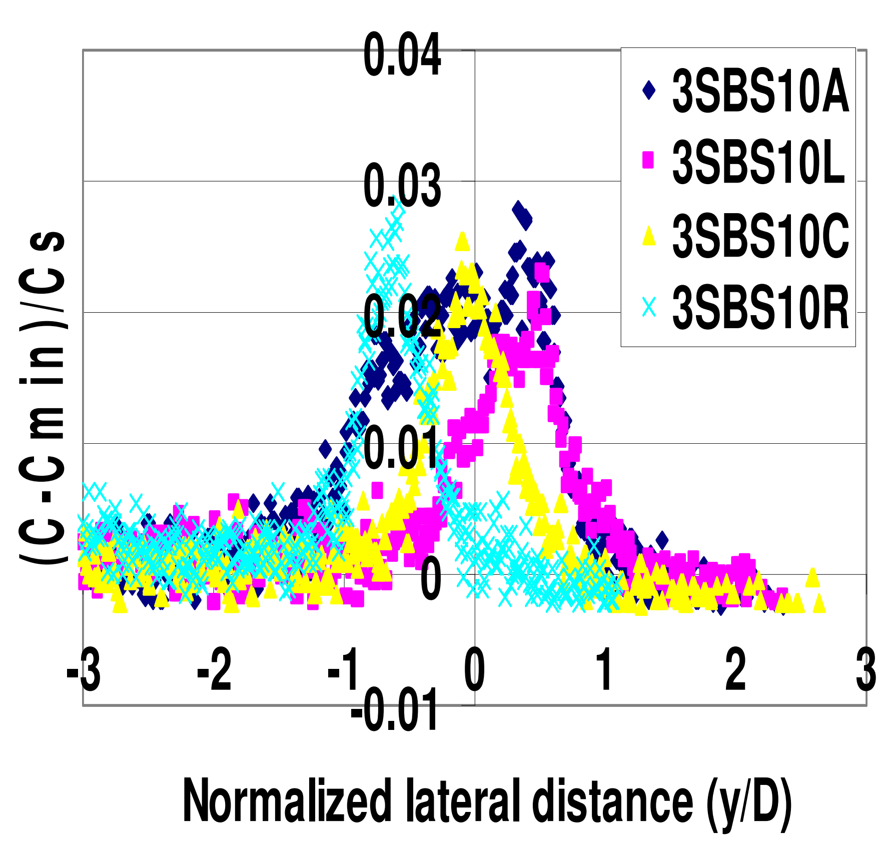


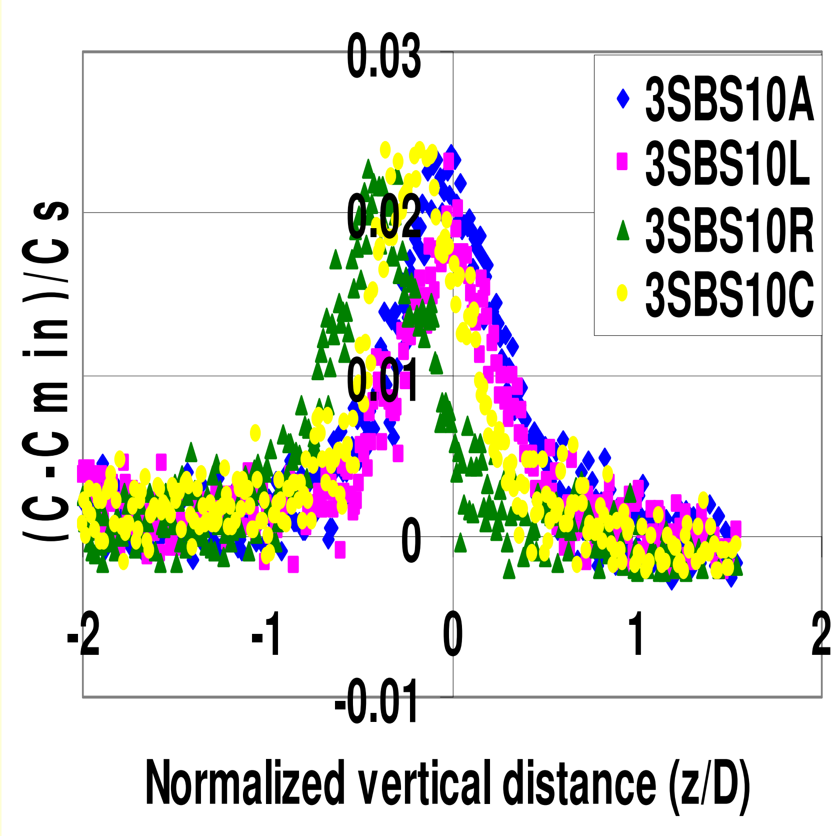
x/D = 34.8

Plume Trajectory Comparison (2SBS)



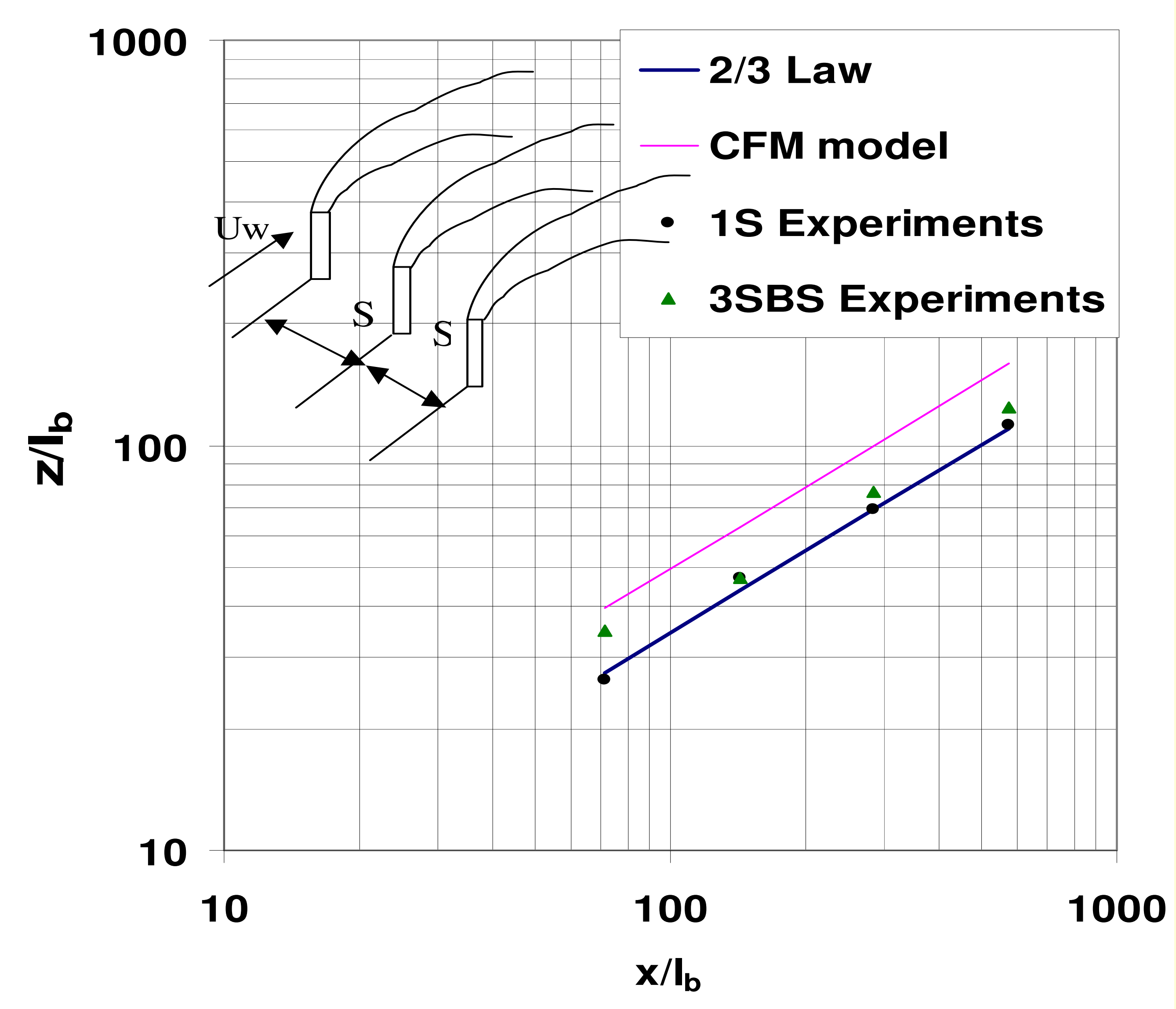
Normalized Gaussian Profiles of Mean Concentration (3SBS)



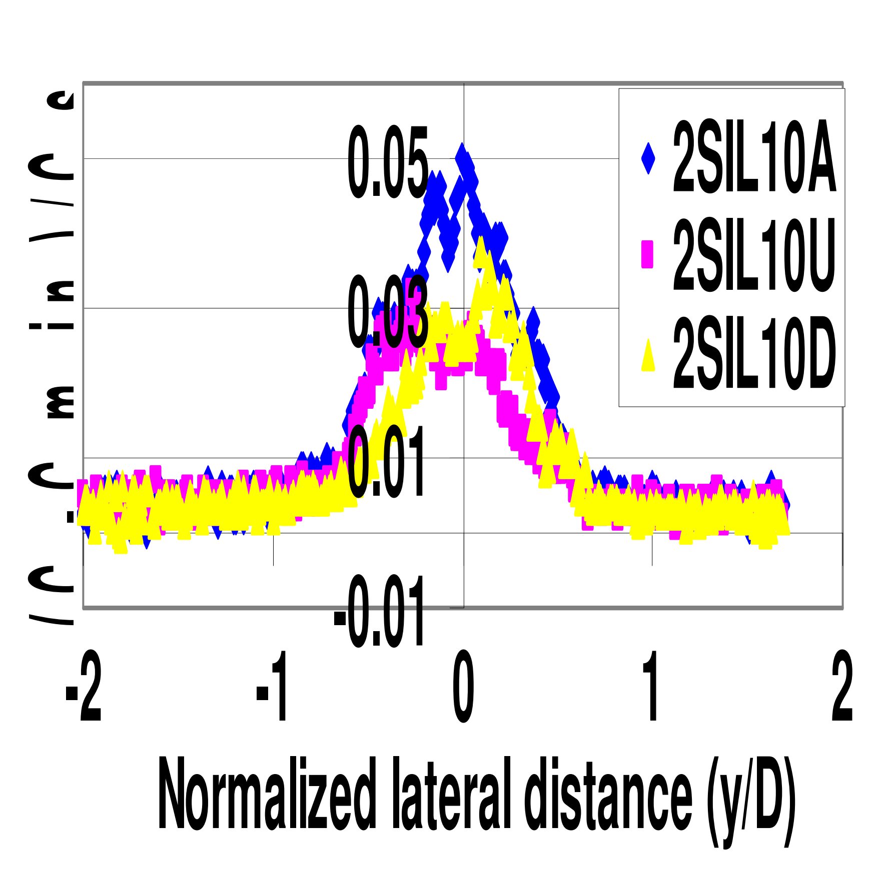


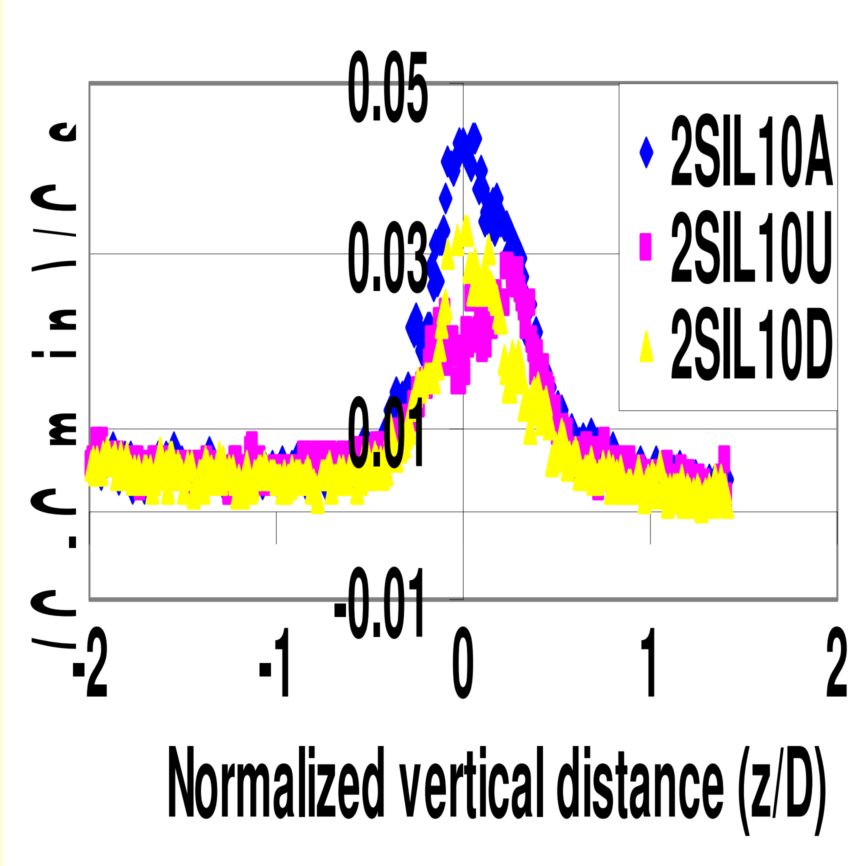
x/D = 8.7

Plume Trajectory Comparison (3SBS)



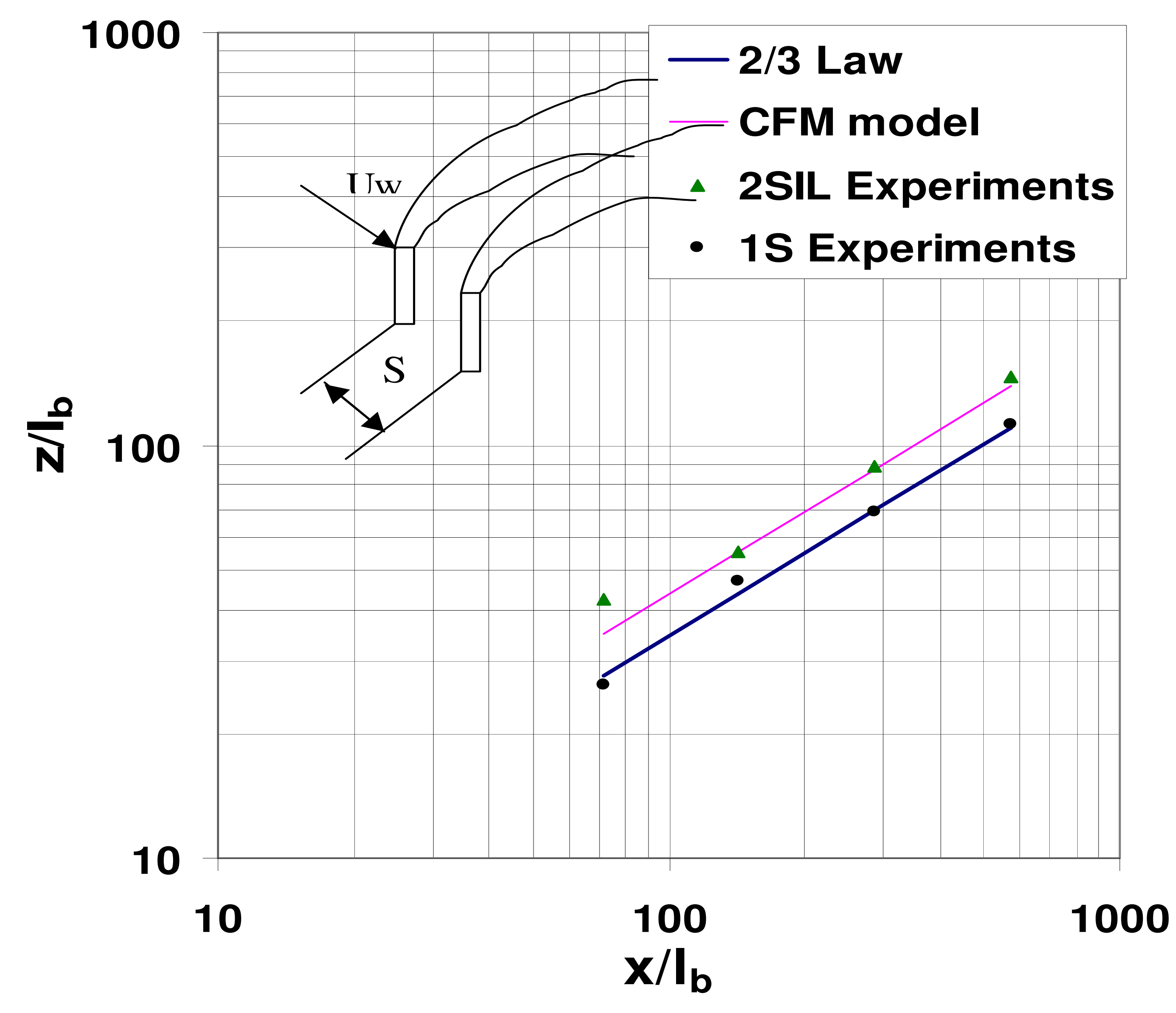
Normalized Gaussian Profiles of Mean Concentration (2SIL)



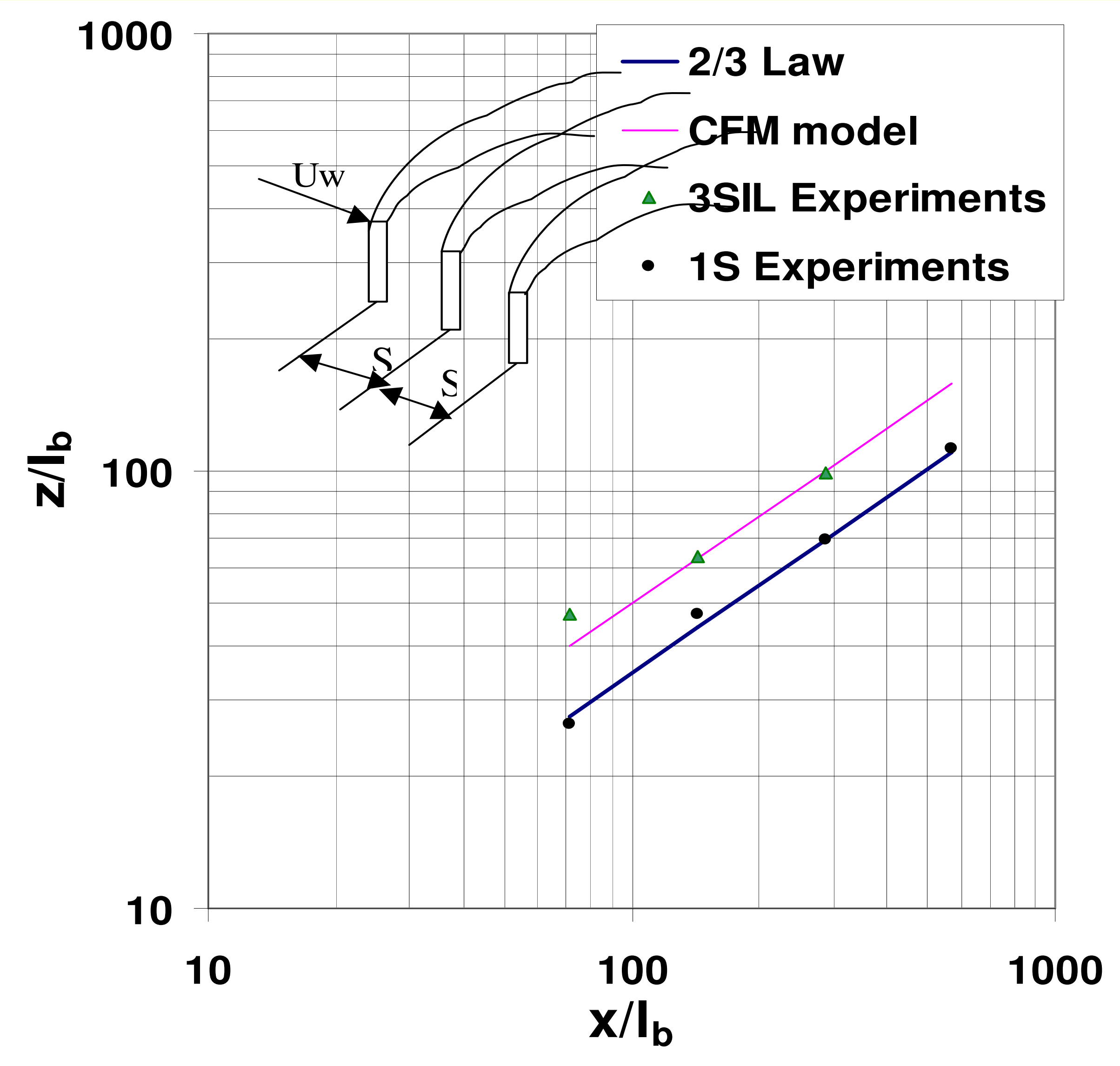


x/D = 8.7

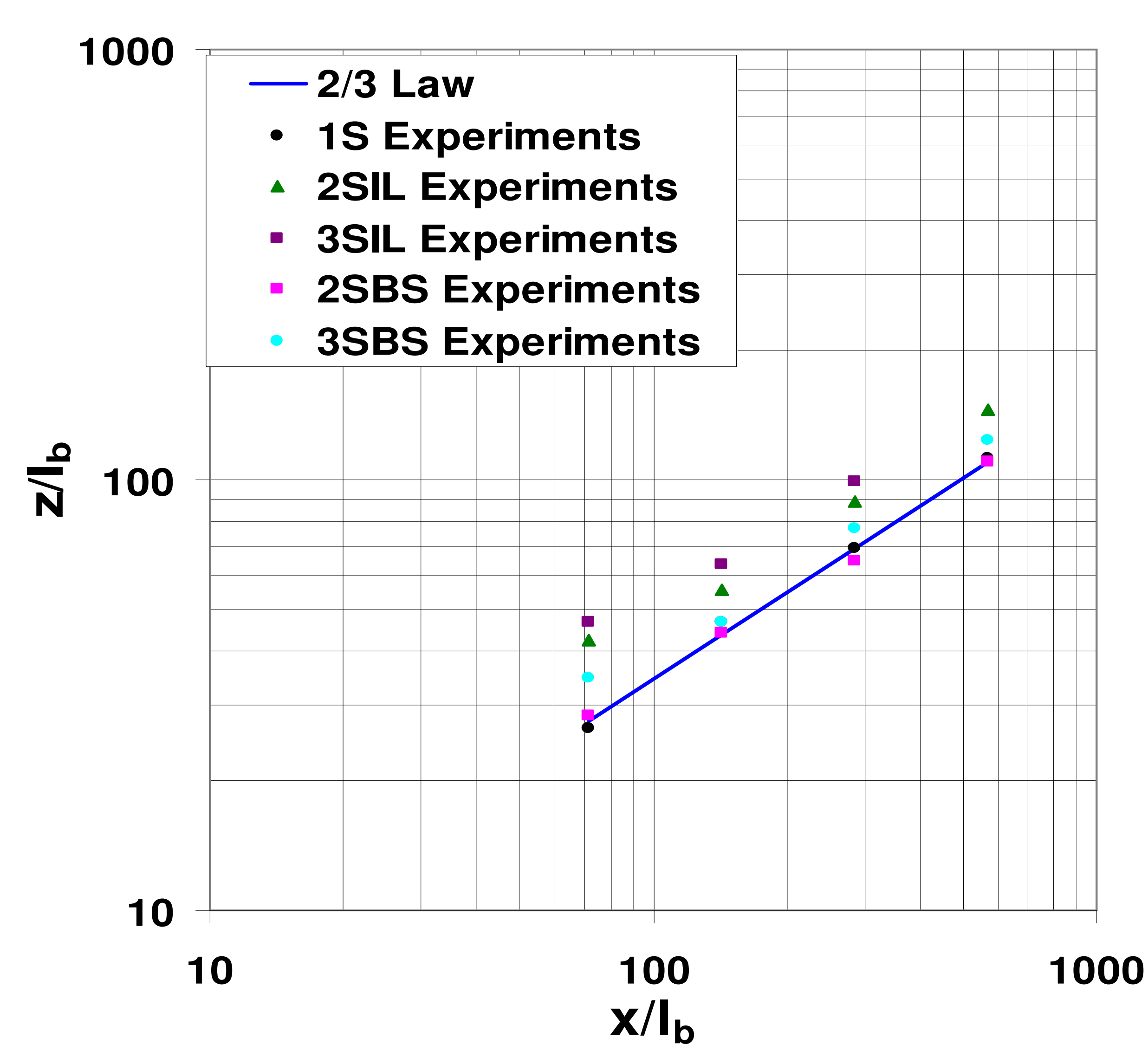
Plume Trajectory Comparison (2SIL)



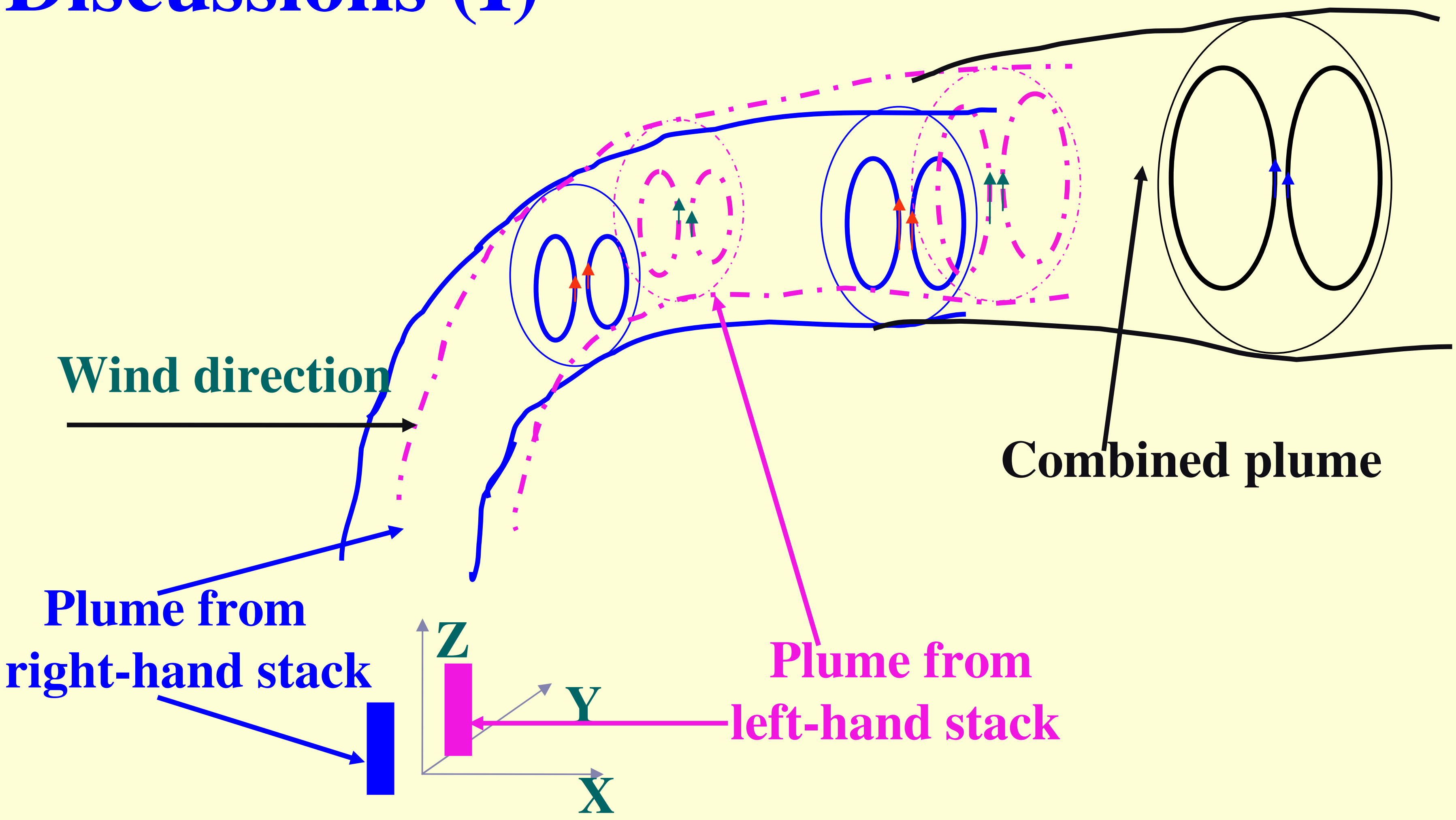
Plume Trajectory Comparison (3SIL)



Plume Trajectory Comparison (all)

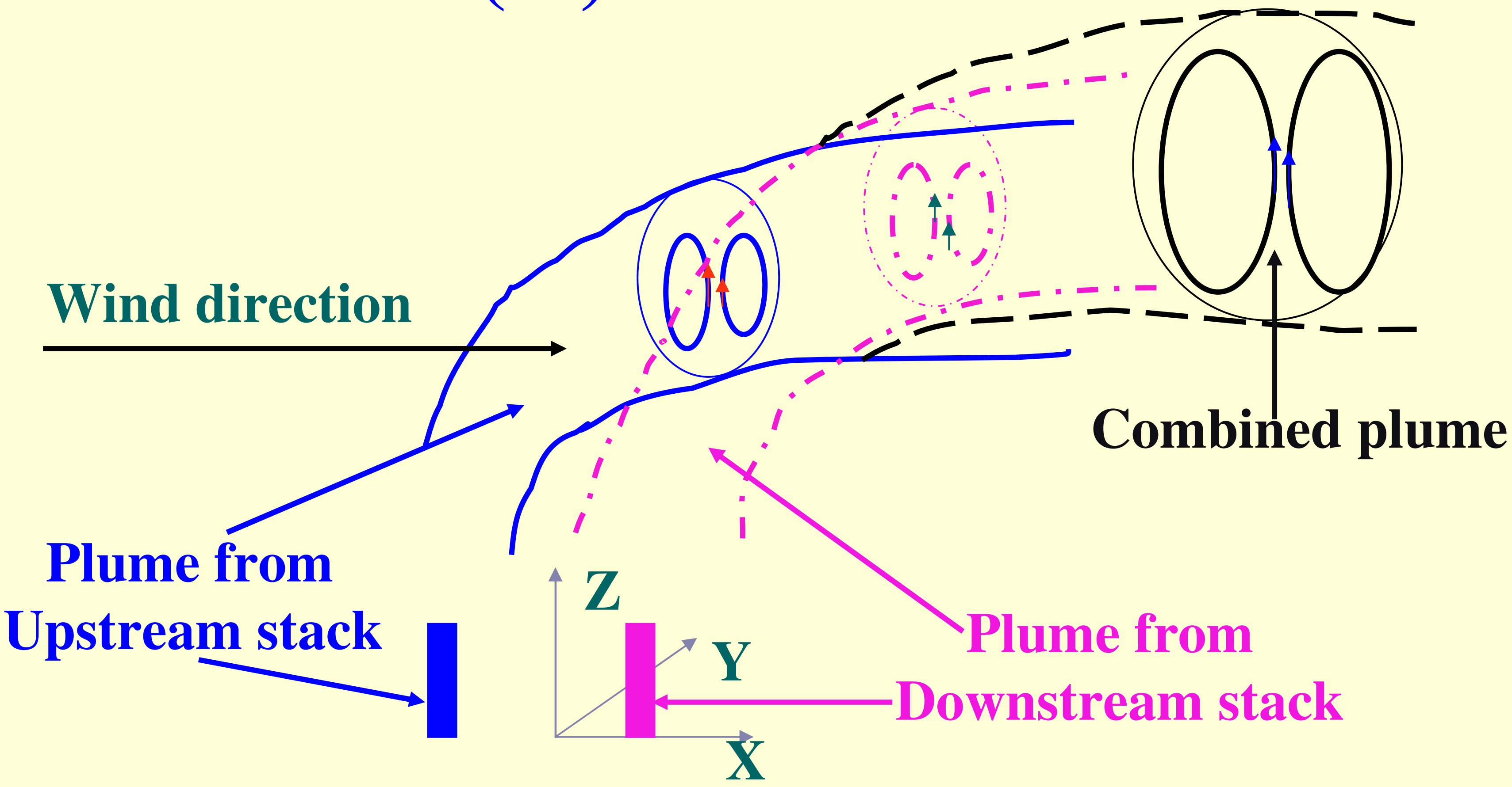


Discussions (I)



Sketch of vortex interactions for two stack side-by-side cases

Discussions (II)



Sketch of vortex interactions and momentum shielding
for two stack in-line cases

Conclusions

1. The PLIF experimental method, implementing an image processing procedure to obtain quantitative concentration information, works very well.
2. Side-by-side Cases: the two plumes have not fully mixed at x/D = 17.4, however, the three plumes have merged at x/D = 8.7.
3. In-line cases: the two plumes have merged together at x/D = 8.7.
4. The CFM model can not accurately predict the trajectories for side-by-side cases; but can accurately predict them for in-line cases.

Further Work

1. The effects of exit velocity ratio and wind angle.
2. The effects of stack array patterns other than in-line and side-by-side cases, e.g., stacks in-circle.
3. A new model needs to be developed for accurately predict the plume trajectory for side-by-side case or a model which can incorporate in-line, side-by-side, in-circle cases together.
4. Quantitatively determining how large are the effects of buoyancy enhancement, momentum shielding, and vorticity interactions.

Acknowledgements

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