Performance Evaluation of Ultrasonic Flow Meters in NIST’s Smokestack Simulator

Liang Zhang

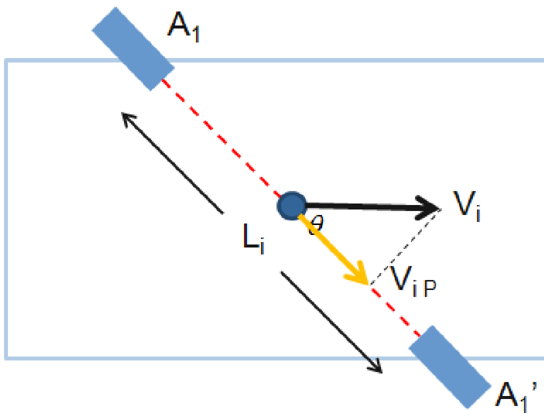
National Institute of Metrology, China

Performance Evaluation of USM in NIST's SMSS

Smokestack Simulator of NIM China

Flue Gas Ultrasonic Flowmeter

Path Velocity



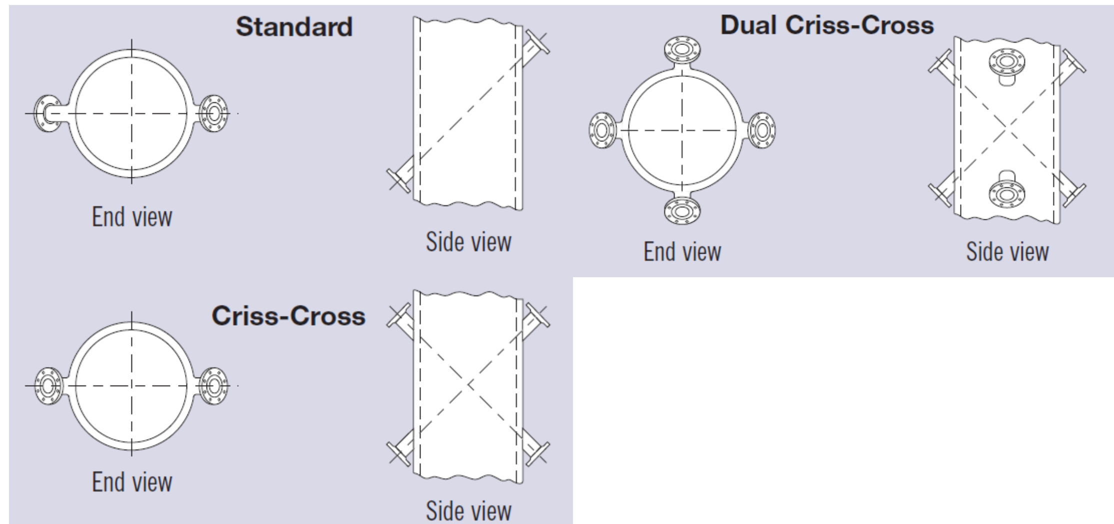
$$c + \overline{v}_i \cos\theta = \frac{L_i}{t_{i,\mathrm{d}}}$$

$$c - \overline{v}_i \cos\theta = \frac{L_i}{t_{i,u}}$$

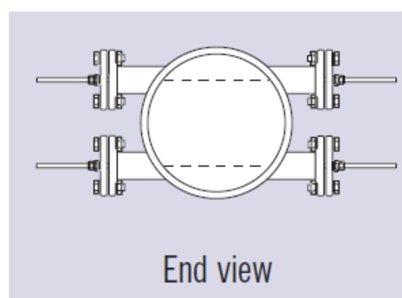
$$\Rightarrow v_i = \frac{L_i}{2\cos\theta_i}\left(\frac{1}{t_{i,d}} - \frac{1}{t_{i,u}}\right)$$

Multi Path USM

Diametric Path



Mid-Radius Path



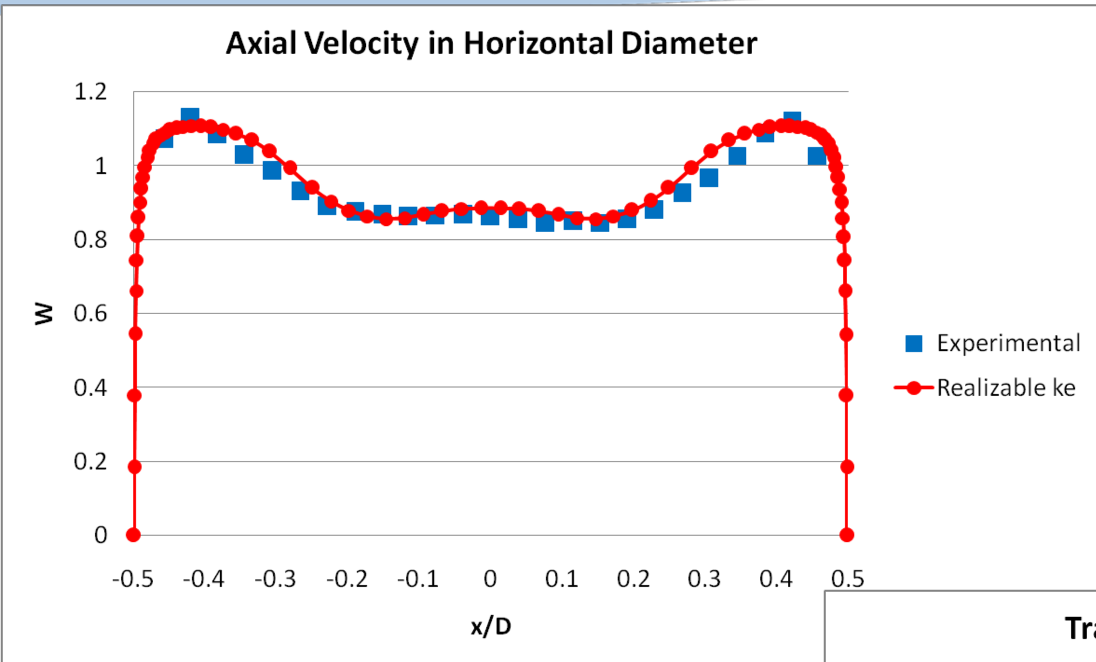
$$q_v = 2R^2 \sum_{i=1}^{N} W_i v_i$$

USM Evaluation Using CFD Simulation

- Calculate the flow field in the SMSS using CFD
- Estimate the performance of different USMs

- Give recommendation for the path layout of spool piece
- Provide users with a reference when selecting USM.
- Use for extrapolate the SMSS test result to real stack.

CFD Simulation Method



ent tetrahedral, 14.7 million

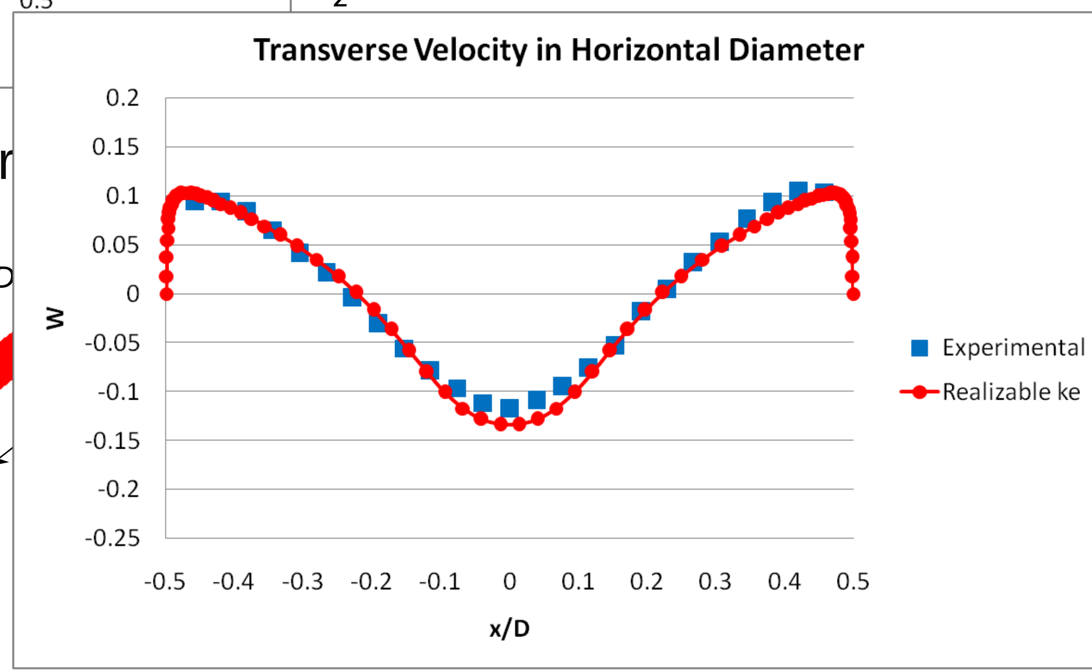
, Y+ around 1

, constant viscosity

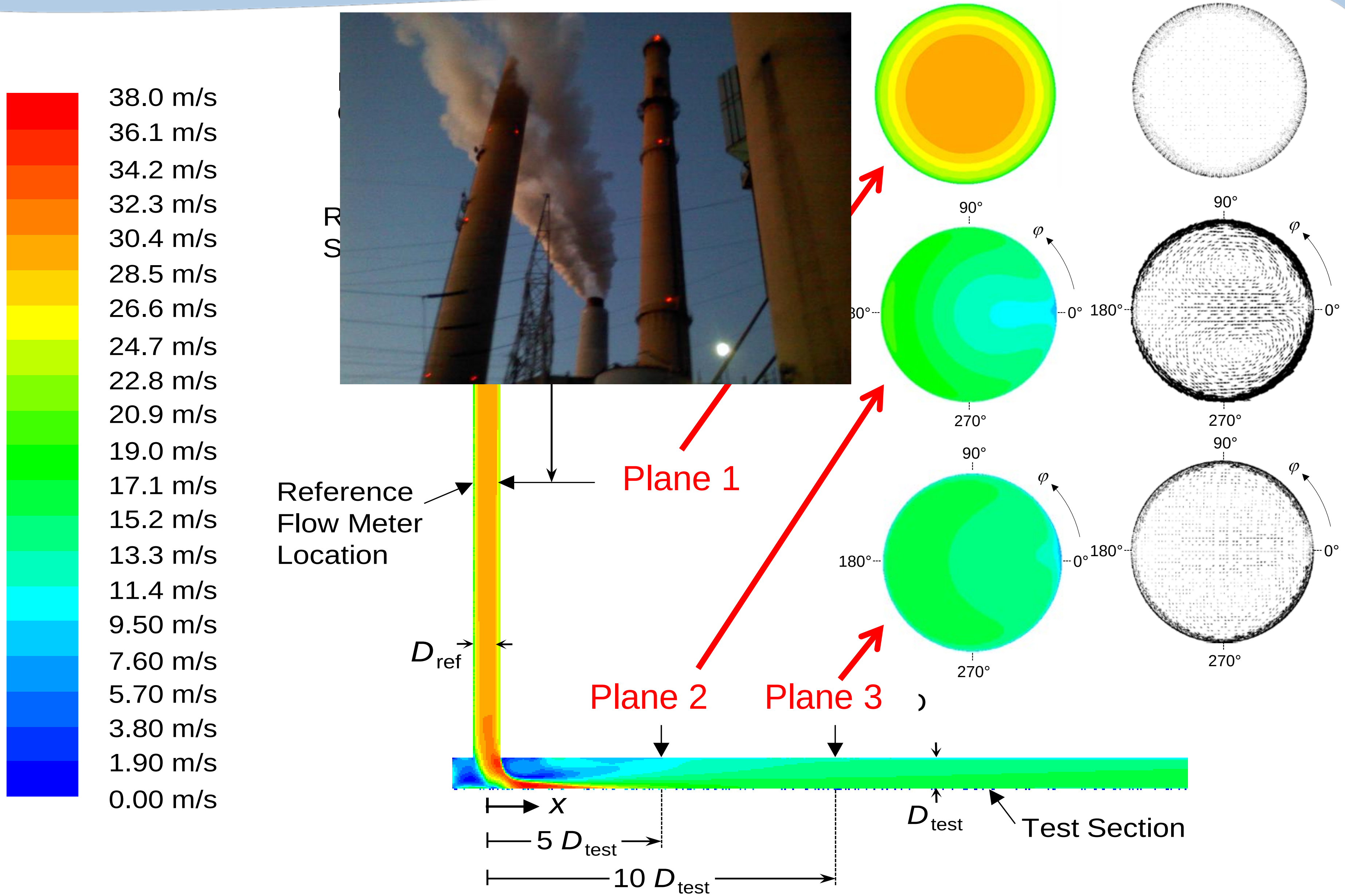
ce Wall Treatment

aust Fan

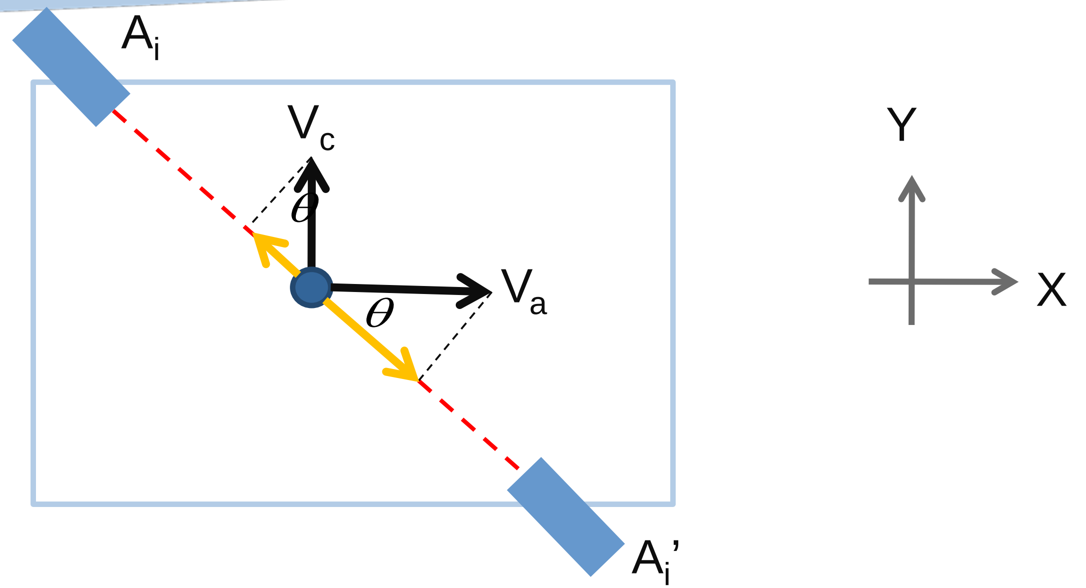
Second order



CFD Flow Field in SMSS



Mid-Radius USM Error Analysis Method



$$E = Q_{\mathrm{USM}} - Q_{\mathrm{act}}$$

$$= \sum_{i=1}^{n} w_i \left(v_{ai} - v_{ci} \tan\theta\right) S_c - Q_{real}$$

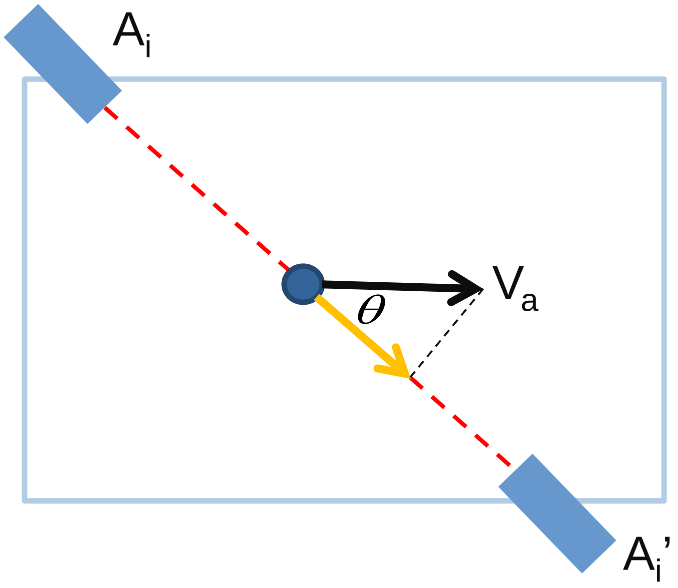
$$= \left(\sum_{i=1}^{n} w_i v_{ai} S_c - Q_{real} \right) - \sum_{i=1}^{n} w_i v_{ci} \tan\theta S_c$$

$$= \left(\sum_{i=1}^{n} w_i v_{ai} S_c - \lim_{m\to\infty} \sum_{j=1}^{m} w_j v_{aj} S_c \right) + \left(\lim_{m\to\infty} \sum_{j=1}^{m} w_j v_{aj} S_c - Q_{real} \right) - \sum_{i=1}^{n} w_i v_{ci} \tan\theta S_c$$

$$= \left(\sum_{i=1}^{n} w_i v_{ai} S_c - \lim_{m\to\infty} \sum_{j=1}^{m} w_j v_{aj} S_c \right) - \lim_{m\to\infty} \sum_{j=1}^{m} w_i v_{cj} \cot\theta S_c - \sum_{i=1}^{n} w_i v_{ci} \tan\theta S_c$$

Mid-Radius USM Error Analysis Method

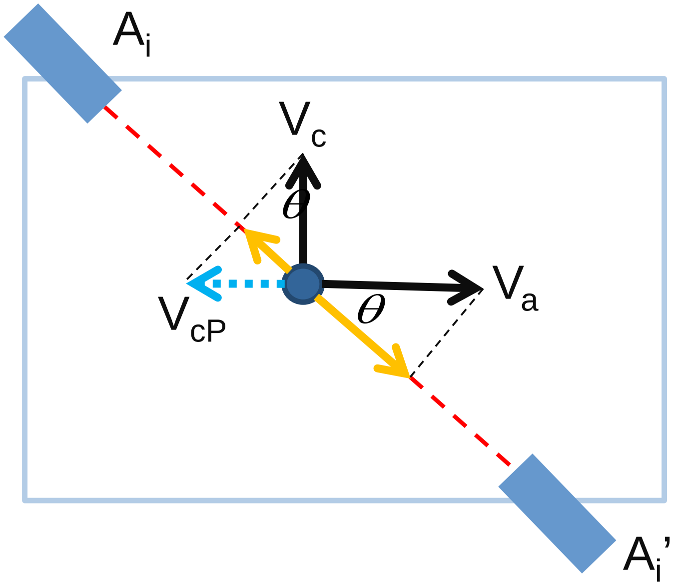
Axial Velocity Integral Error



$$E_1 = \sum_{i=1}^{n} w_i v_{ai} S_c - \lim_{m\to\infty} \sum_{j=1}^{m} w_j v_{aj} S_c$$

Mid-Radius USM Error Analysis Method

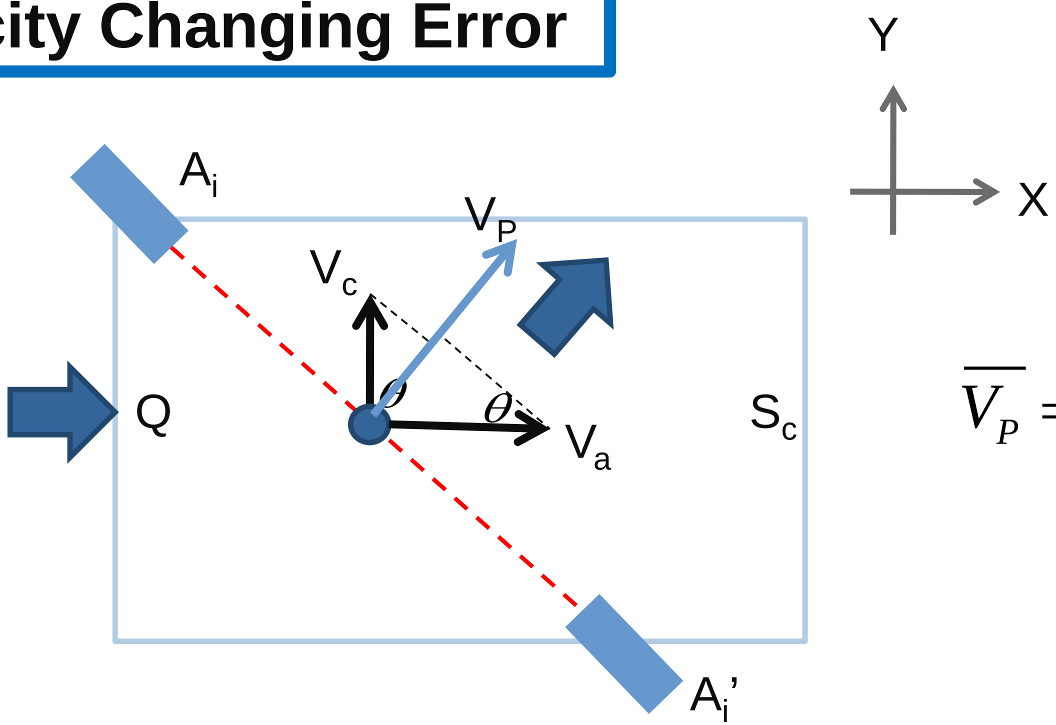
Transverse Flow Projection Error



$$E_3 = -\sum_{i=1}^{n} w_i v_{ci} \tan\theta S_c$$

Mid-Radius USM Error Analysis Method

Axial Velocity Changing Error

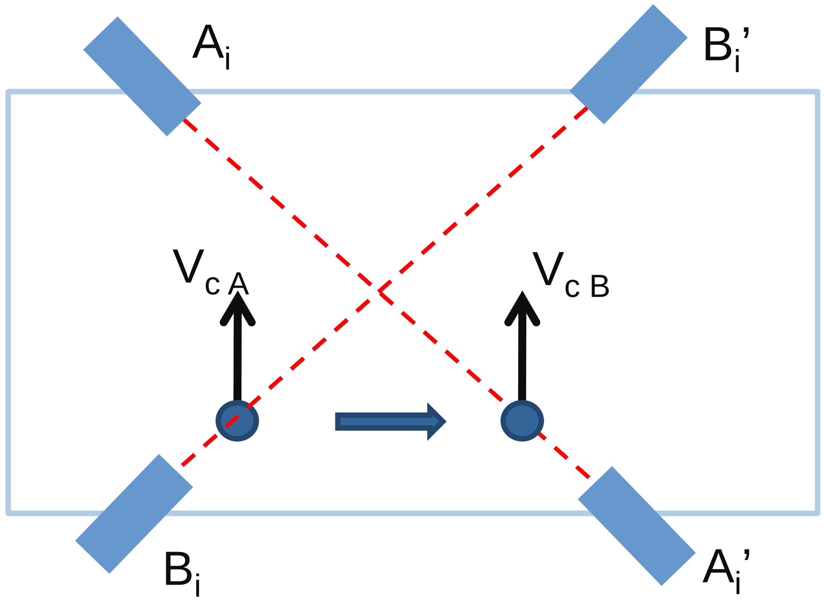


$$\overline{V_P} = \frac{Q}{S_c / \sin\theta}$$

$$E_2 = -\lim_{m\to\infty}\sum_{j=1}^{m} w_i v_{cj} \cot\theta S_c$$

Mid-Radius USM Error Analysis Method

Cross Path/Plane Compensation

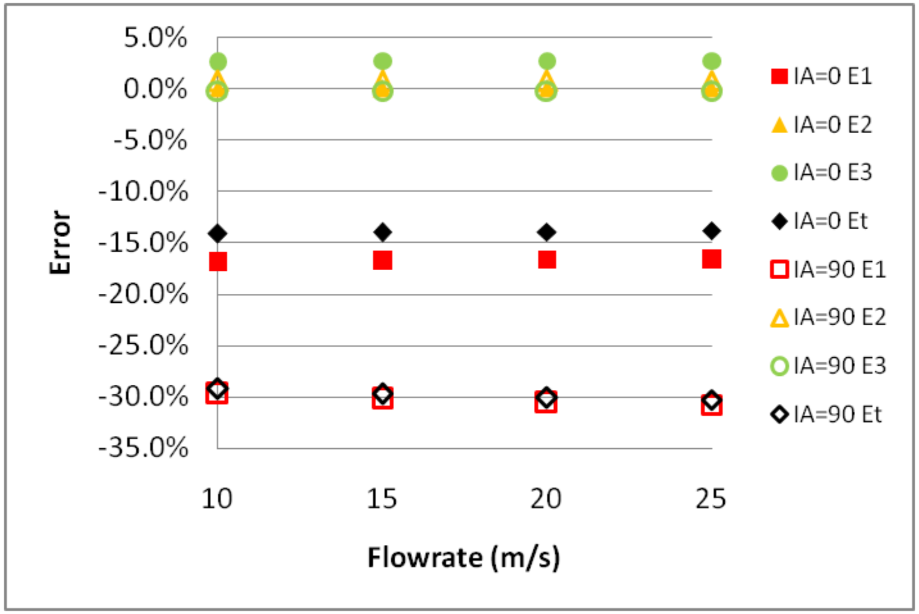


$$E_{AB} = \underbrace{\frac{E_{1,A} + E_{1,B}}{2}}_{E_{1,AB}} + \underbrace{\lim_{m \to \infty} \sum_{j=1}^{m} w_j \frac{v_{cj}^{B} - v_{cj}^{A}}{2} \cot\theta S_c}_{E_{2,AB}} + \underbrace{\sum_{i=1}^{n} w_i \frac{v_{ci}^{B} - v_{ci}^{A}}{2} \tan\theta S_c}_{E_{3,AB}}$$

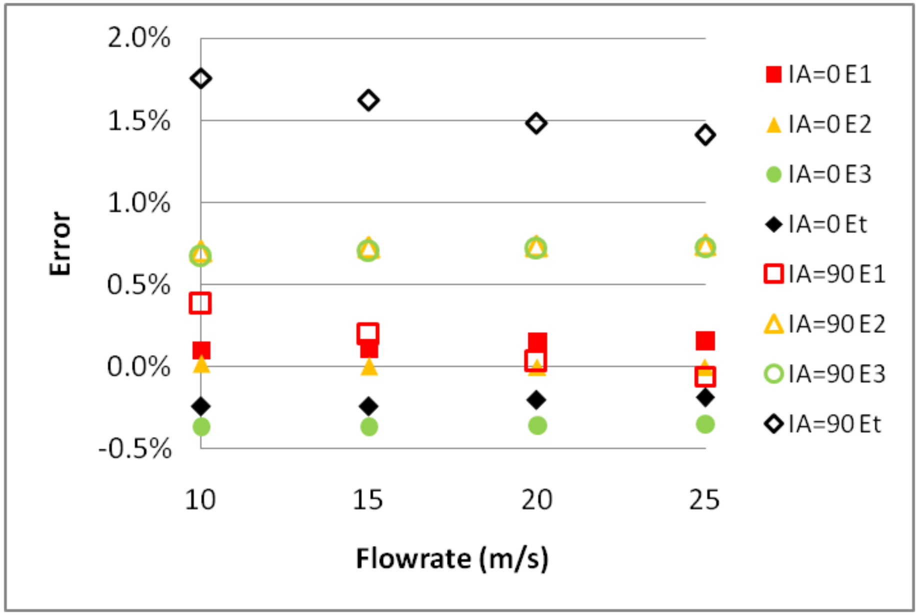
Velocity Impact on Measurement

- In the velocity range of 10m/s to 25m/s, velocity dose not have obvious impact on USMs measurement errors

Cross Path Diametric USM



4*2 Path Mid-Radius USM (Gauss-Jacobi)



Flow Profile Correction Factor

Flow profile correction factors (FPCF)

$$K_1 = 1 + 0.2488 \cdot \mathrm{Re}^{-\frac{1}{8}} \left(3\times10^3 \le \mathrm{Re} \le 10^6\right)$$

L. C. Lynnworth, 1989

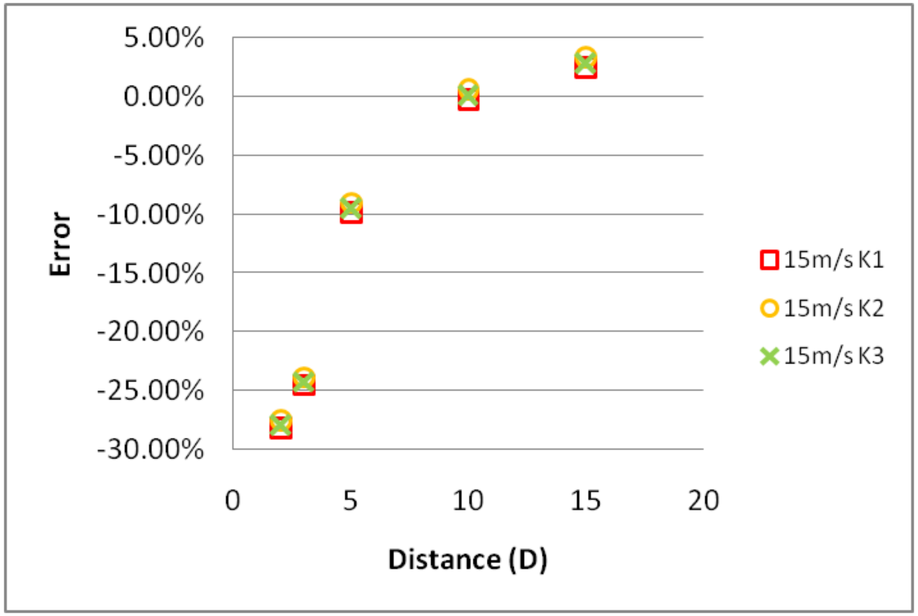
$$K_2 = 1.119 - 0.011 \cdot \log(\mathrm{Re}) \left(3\times10^3 \le \mathrm{Re} \le 5\times10^6\right)$$

J. C. Jung et al., 2000

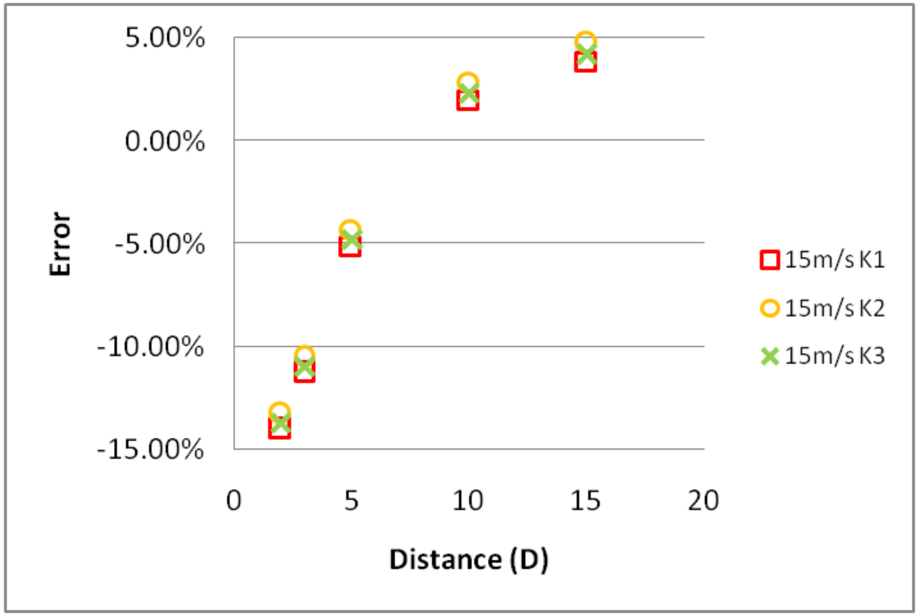
$$K_3 = 1 + 0.01\sqrt{6.25 + 431 \cdot \mathrm{Re}^{-0.237}} \left(3\times10^3 \le \mathrm{Re} \le 10^6\right)$$

Korean Nuclear Society, 2001

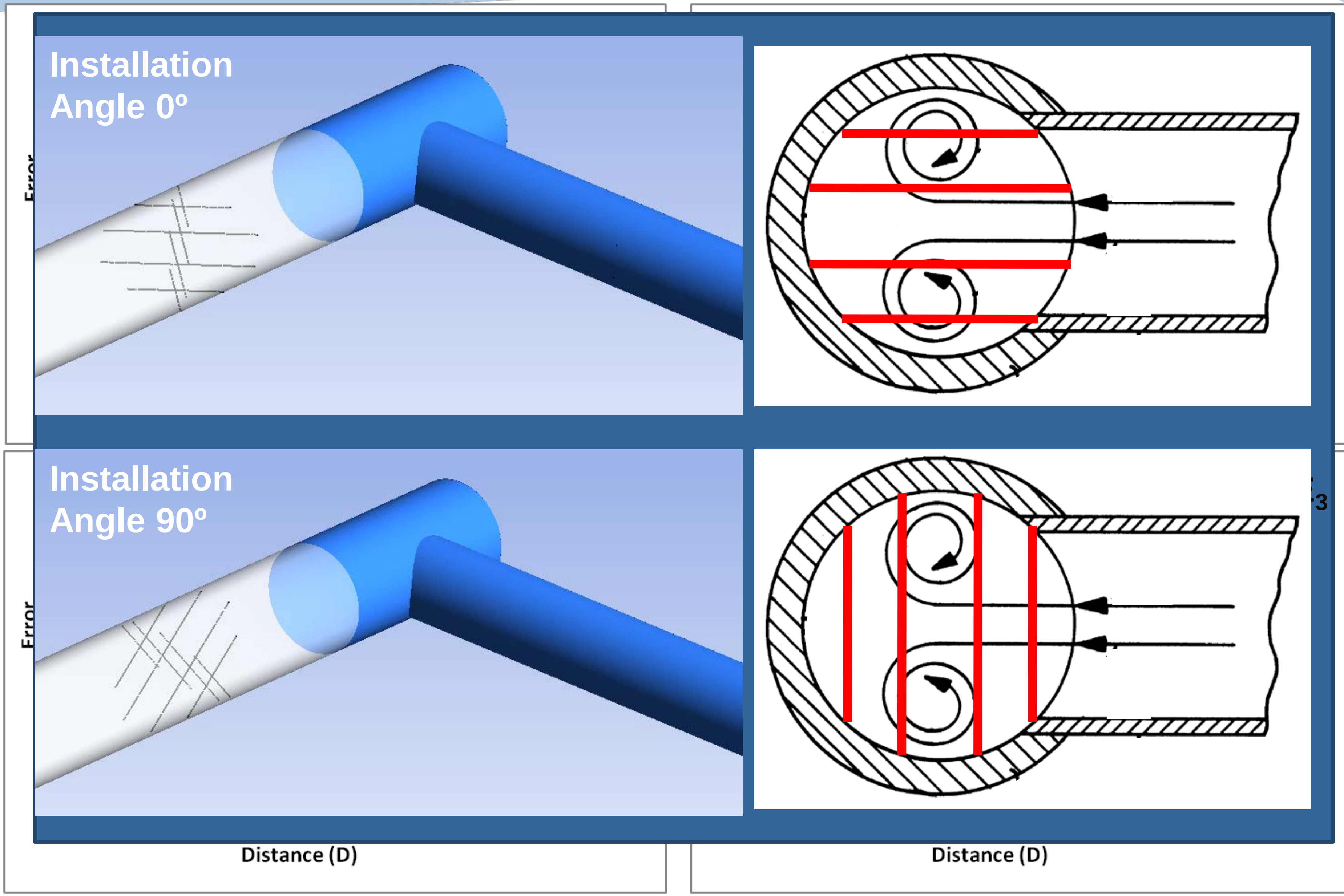
PA45º, A Single Path IA=0º



PA45º, AB Cross-Path IA=0º



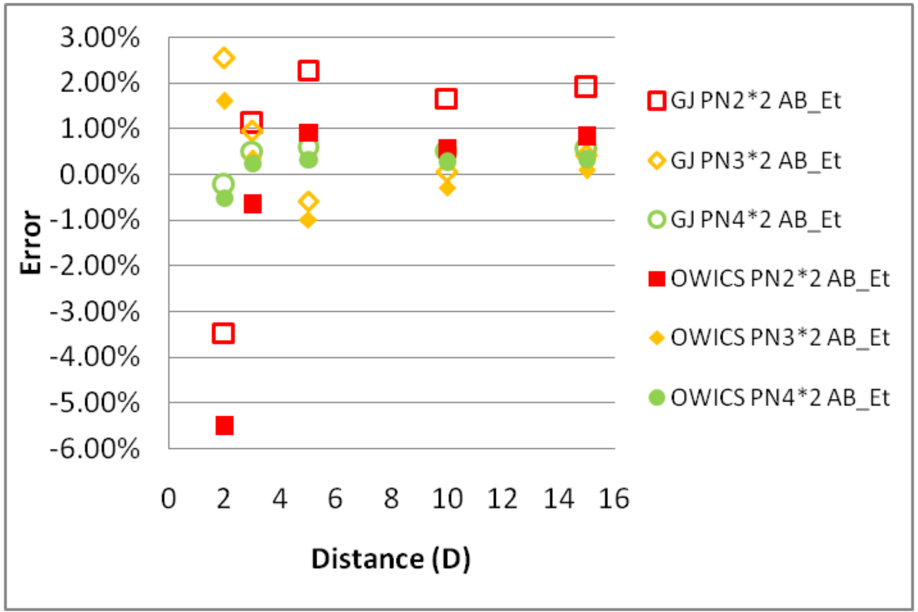
Error Analysis of Diametric USMs



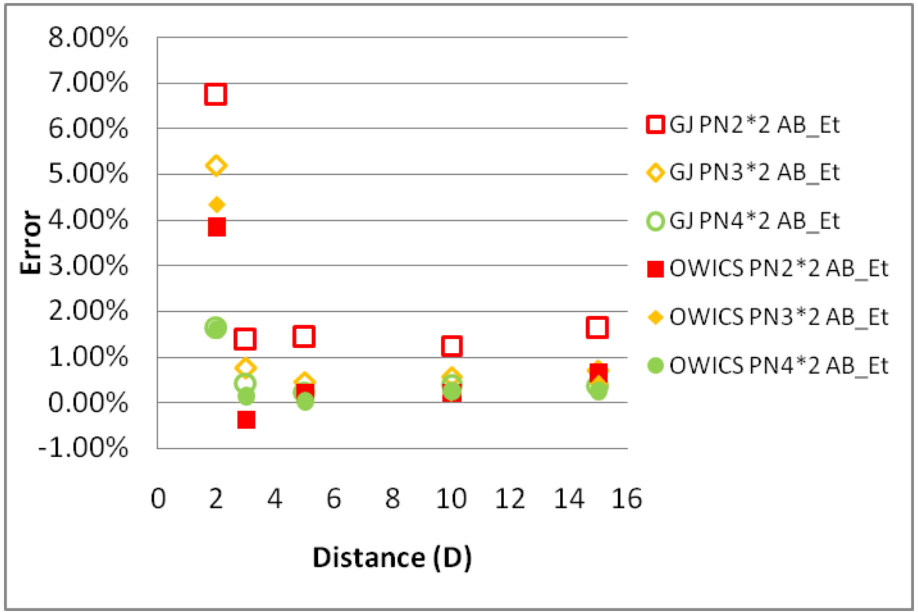
Integration Methods for Mid-Radius USMs

- Gauss-Jacobi and Optimized Weighted Integration for Circular Section (OWICS) are the most accurate integration method for USMs in circular pipes.
- For 2*2 path USM, the measurement error of OWICS USMs decrease quicker than Gauss-Jacobi USMs.

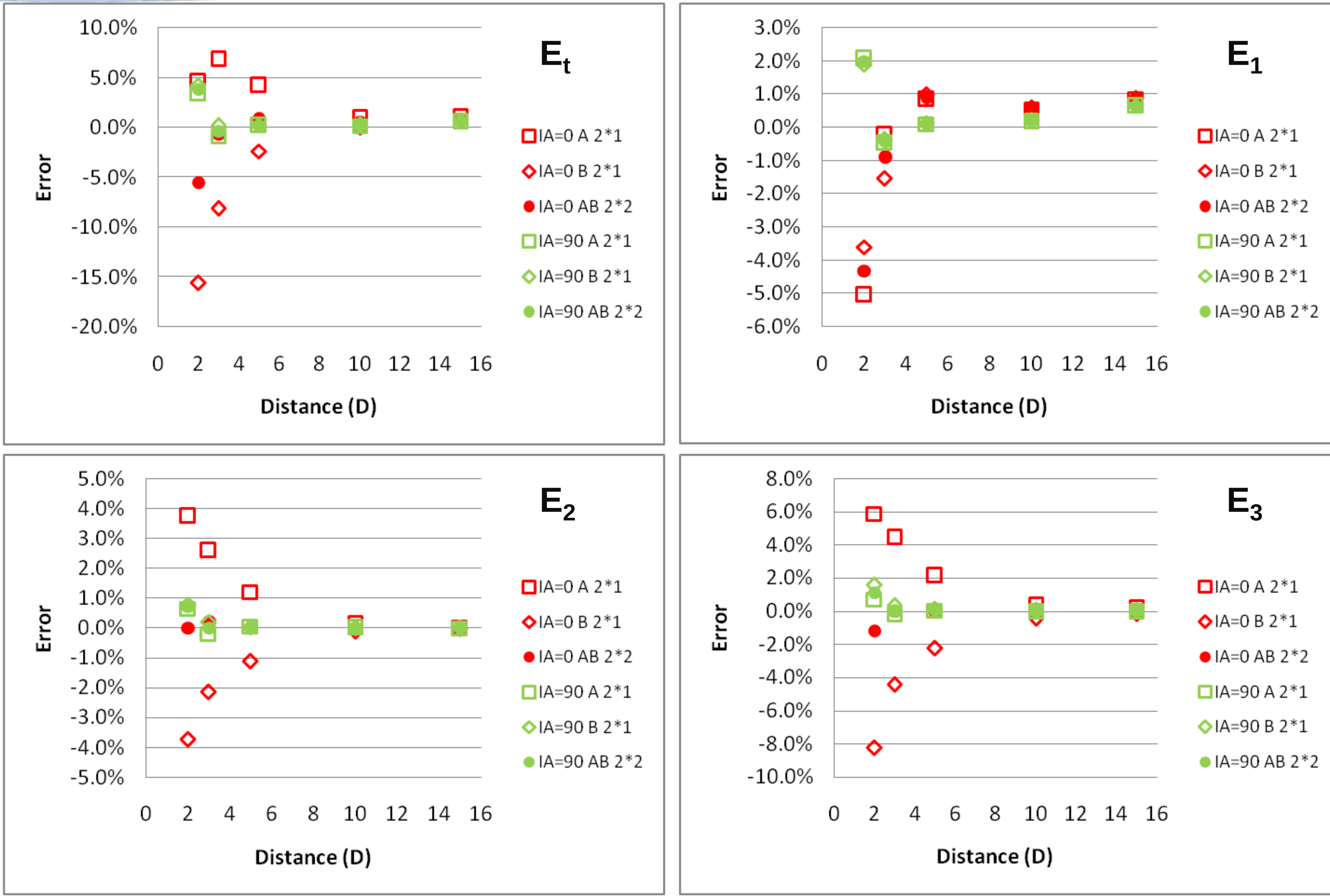
Path Angle 45º, 15m/s, **IA=0º**



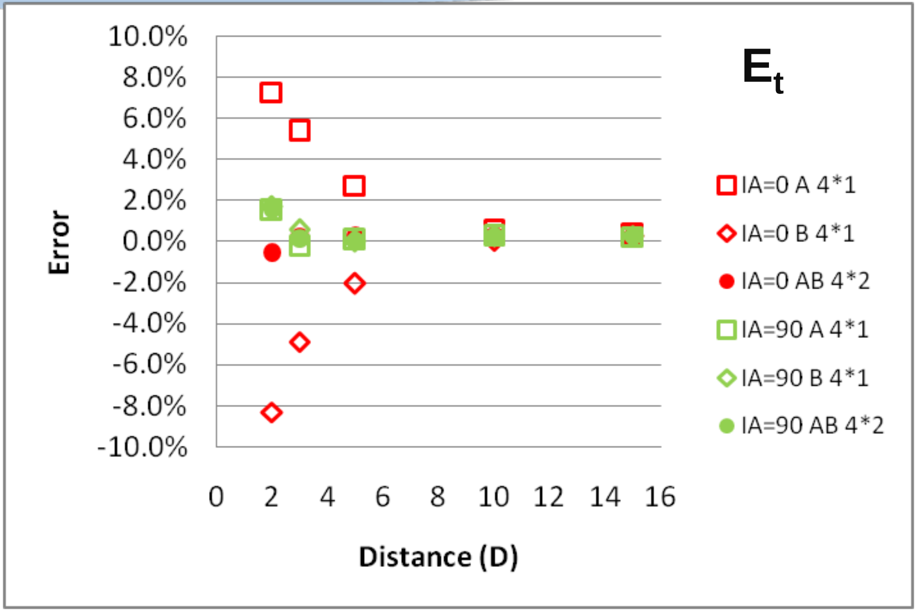
Path Angle 45º, 15m/s, **IA=90º**

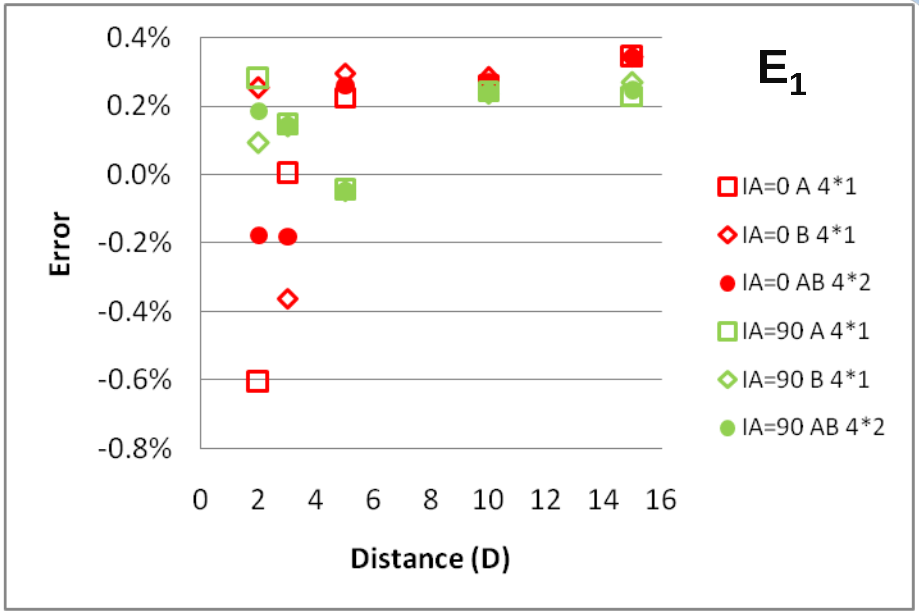


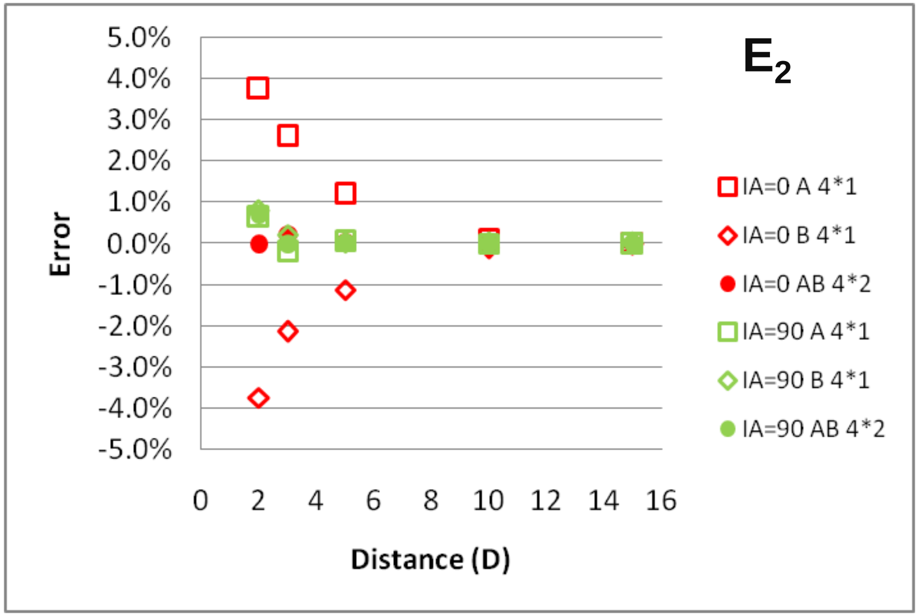
Error Analysis of Mid-Radius USMs–PN 2&4

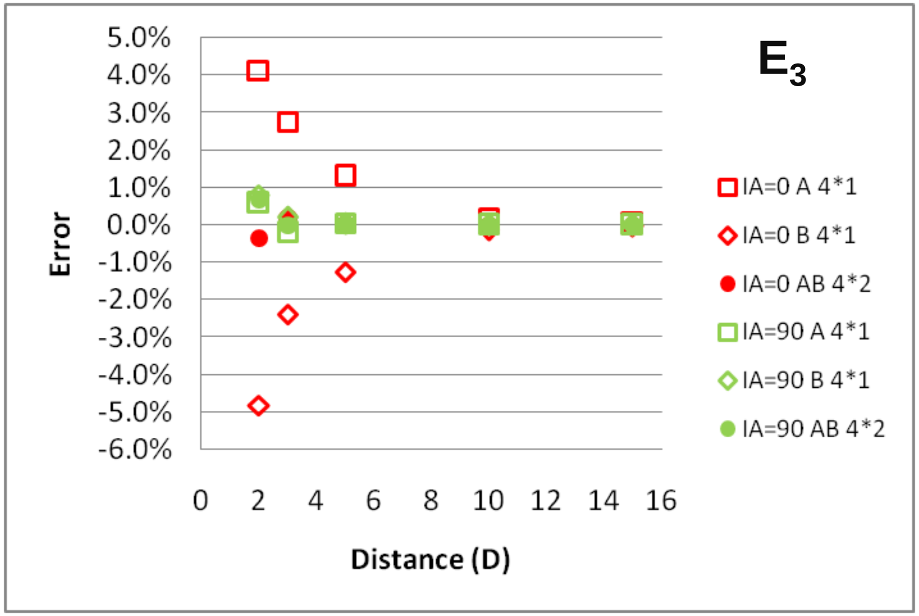


Error Analysis of Mid-Radius USMs–PN 4&8







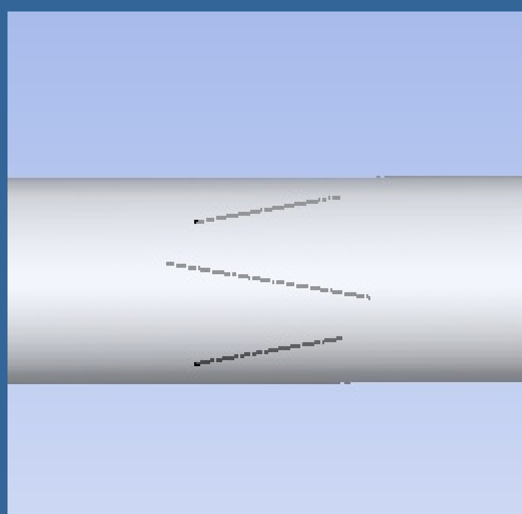


Error Analysis of Mid-Radius USMs–PN 3&6

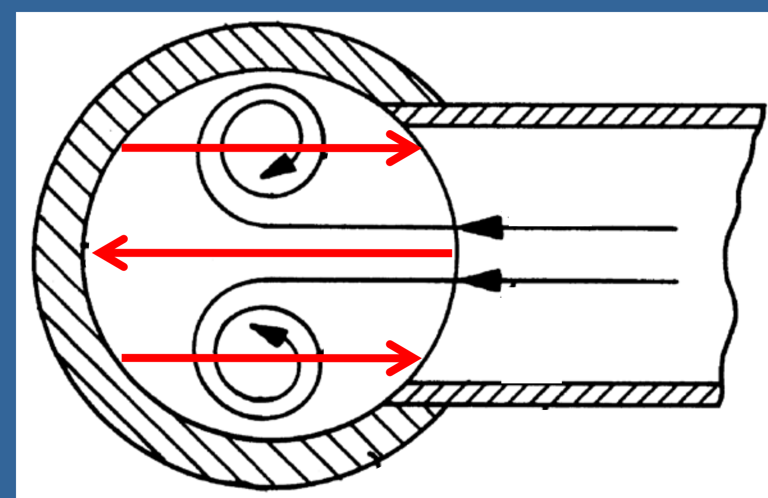
- Staggered path USMs transverse flow error compensation effects depend on the flow field in the pipe and path layout.

OWICS, Path Angle 45º, 15m/s

IA=0º Et



IA=90º Et

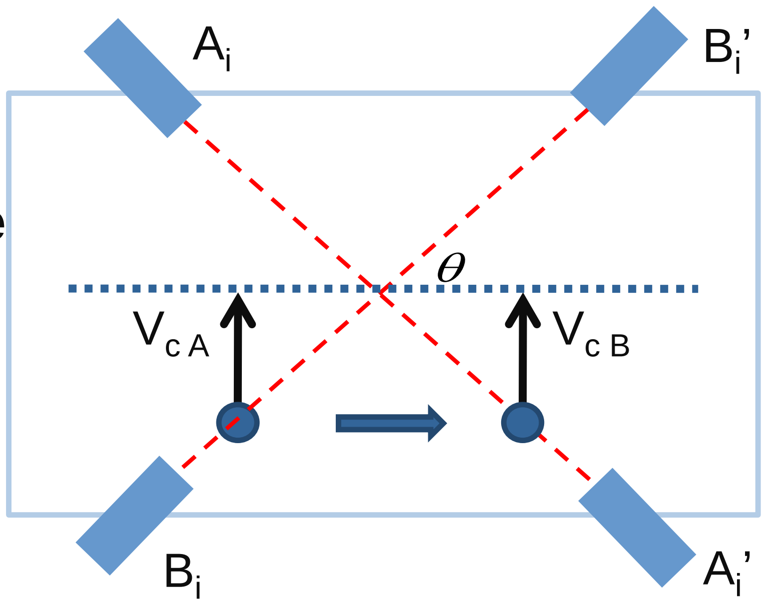


Impact of USM Path Angle

$$E=\left(\sum_{i=1}^{n} w_i v_{ai} S_c-\lim_{m\to\infty}\sum_{j=1}^{m} w_j v_{aj} S_c\right)-\lim_{m\to\infty}\sum_{j=1}^{m} w_i v_{cj}\cot\theta S_c-\sum_{i=1}^{n} w_i v_{ci}\tan\theta S_c$$

$$\approx\left(\sum_{i=1}^{n} w_i v_{ai} S_c-\lim_{m\to\infty}\sum_{j=1}^{m} w_j v_{aj} S_c\right)-2\sum_{i=1}^{n}\frac{w_i v_{cj} S_c}{\sin 2\theta}$$

- **E_1 of different path angle USM depend on the flow field in the pipe**
- **2-4 path single plane USM may have the minimum absolute E_2+E_3 in 45º path angle**
- **For cross-plane USM, the E_2+E_3 can be partially or completely canceled out, it depends on the distribution of transverse velocity in the pipe.**



Conclusion

- Flowrate have little effect on the measurement errors of diametric path and mid-radius path USMs
- USMs measurement errors reduced with the increase of upstream straight pipe length
- Using cross-plane or cross-path USM configuration, measurement errors introduced by transverse flow can be totally or partially compensate
- Optimization of the USM installation angle will reduce the transverse flow velocity component in the path, especially for a single plane USM
- Diametric USMs integration errors are significantly greater than the mid-radius USMs

Conclusion

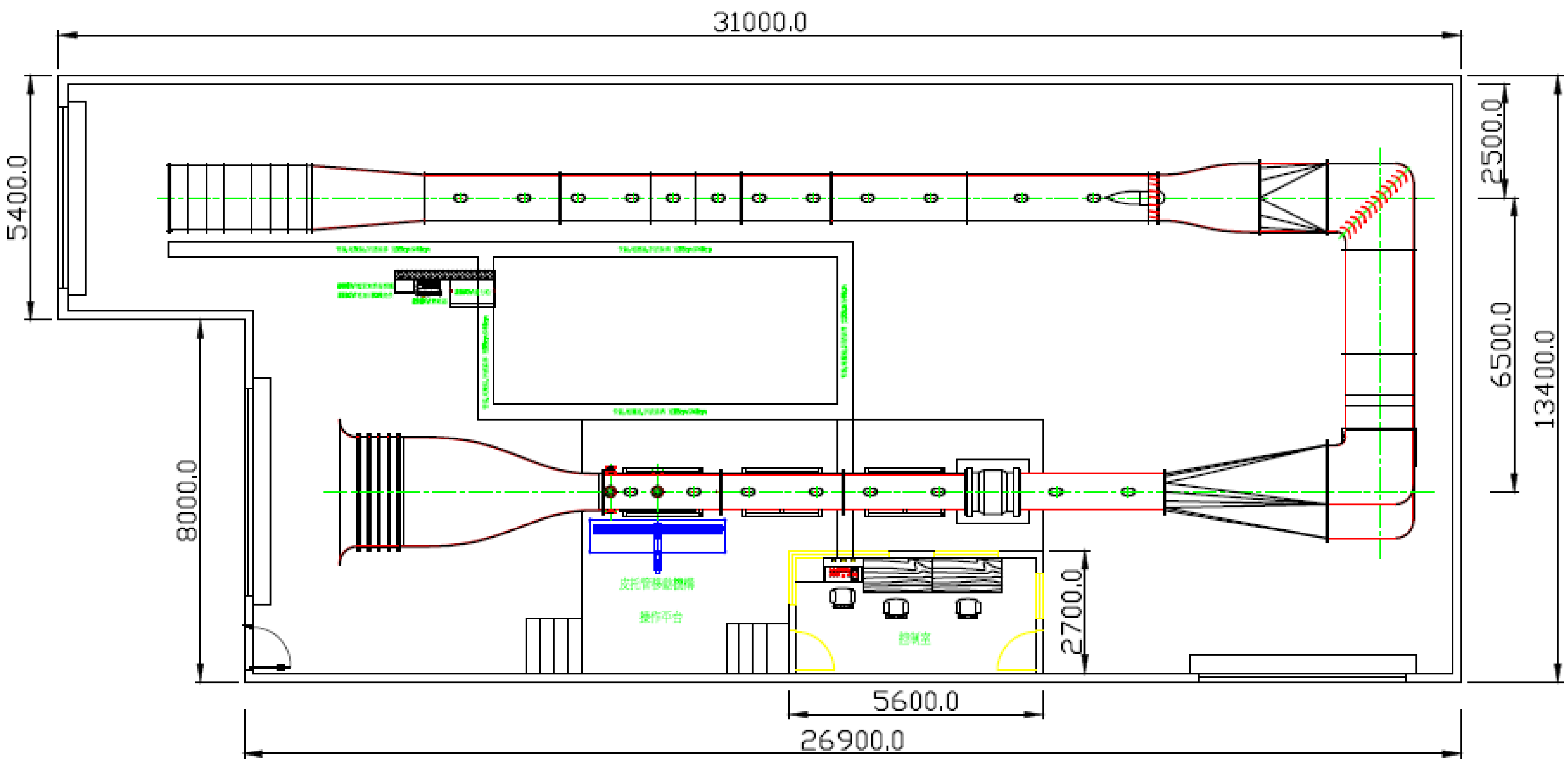
- **For diametric USMs, using dual cross-path do not obviously enhance the USM performance compared to cross-path USM.**
- **Overall, the measurement errors of OWICS USMs are lower than Gauss-Jacobi USMs, especially when the path number is low**
- **Mid-radius path USMs measurement errors decrease with the path number increase**
- **For a single-plane USM, usually in 45º path angle, measurement error introduced by the transverse flow may reach the smallest value.**
- **Recommendation for spool piece: cross plane mid-radius USM using OWICS integration method**

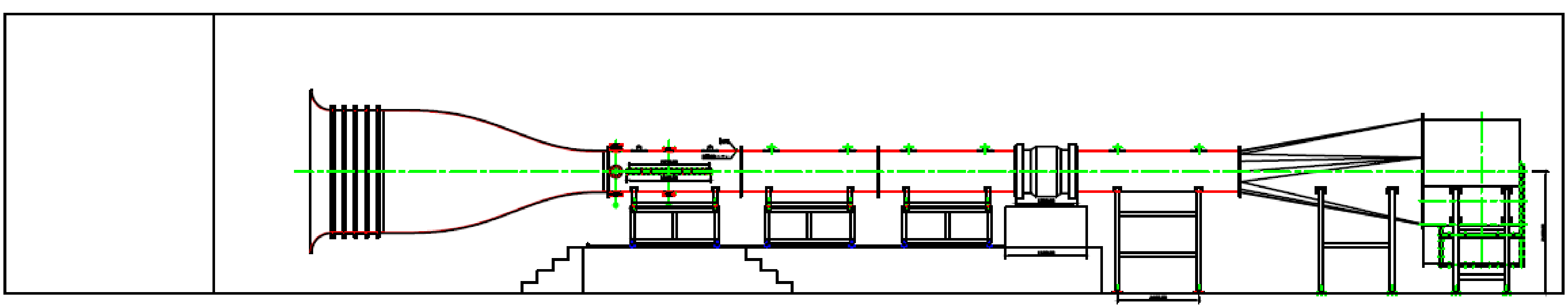
Performance Evaluation of USM in NIST’s SMSS

Smokestack Simulator of NIM China

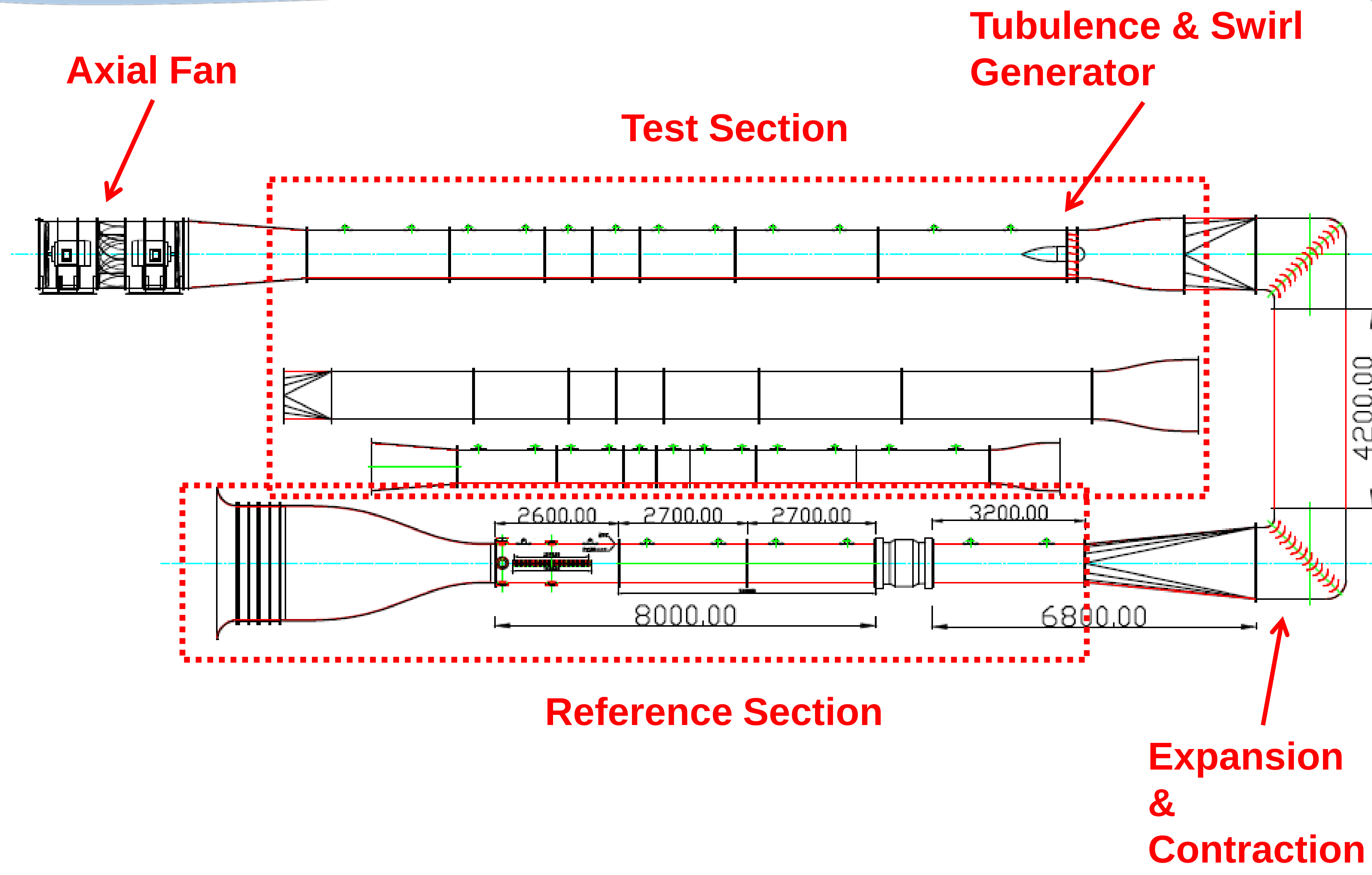
Smoke Stack Simulator of NIM

Smoke Stack Simulator of NIM

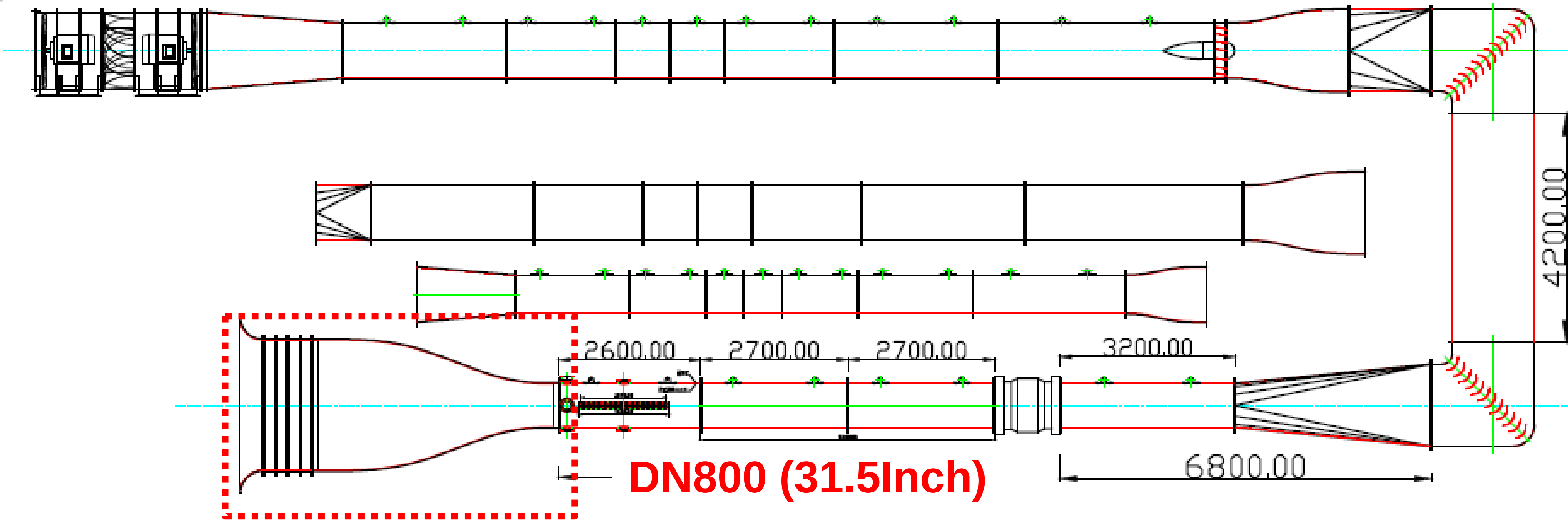




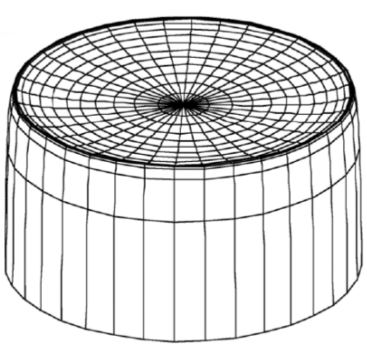
Components Smoke Stack Simulator

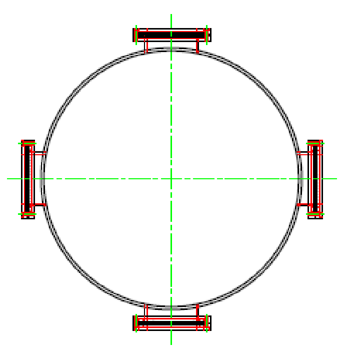


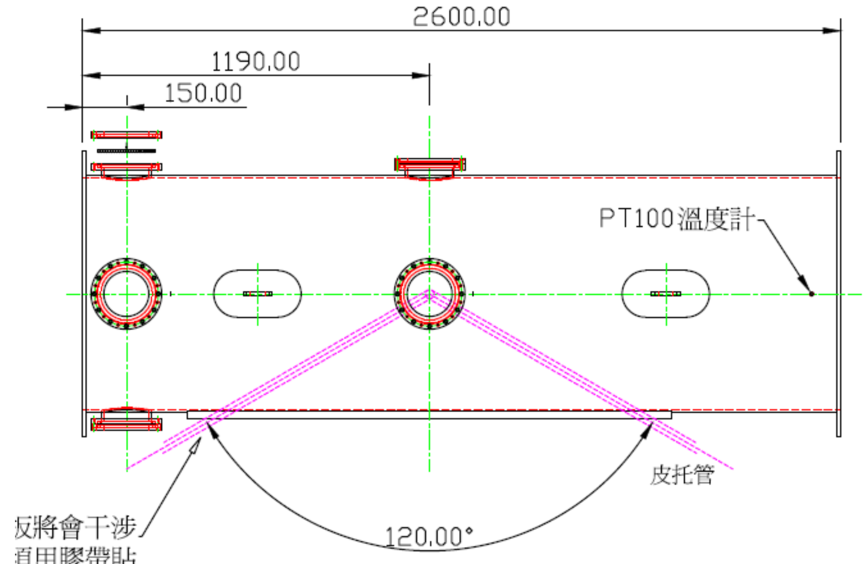
Primary Standard



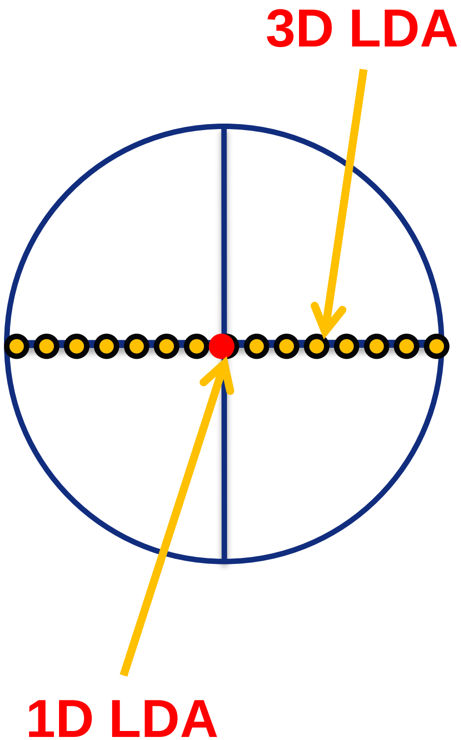
Dual LDA Primary Standard

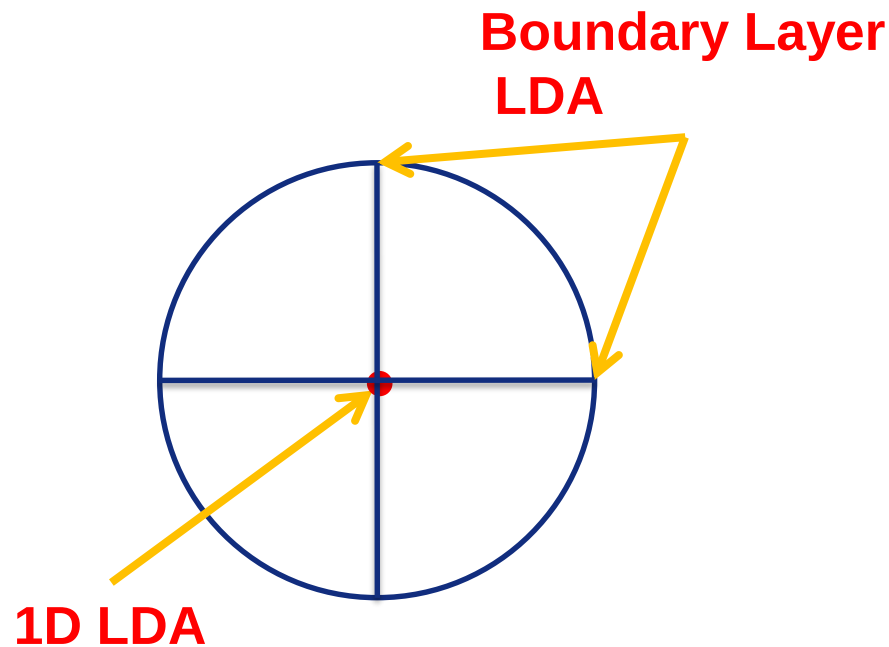


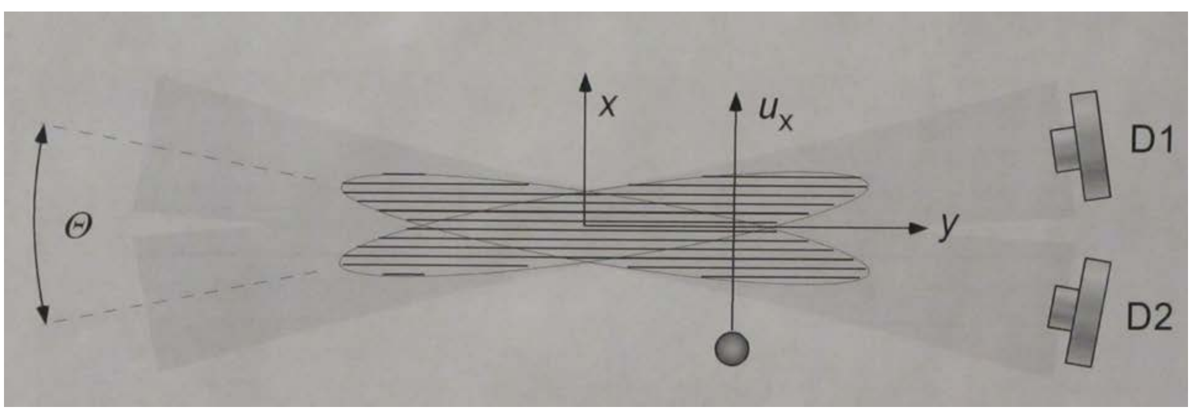


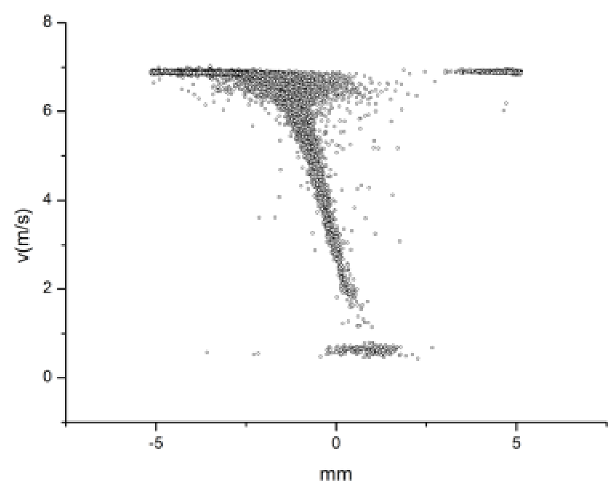


LDA Velocity Area Method

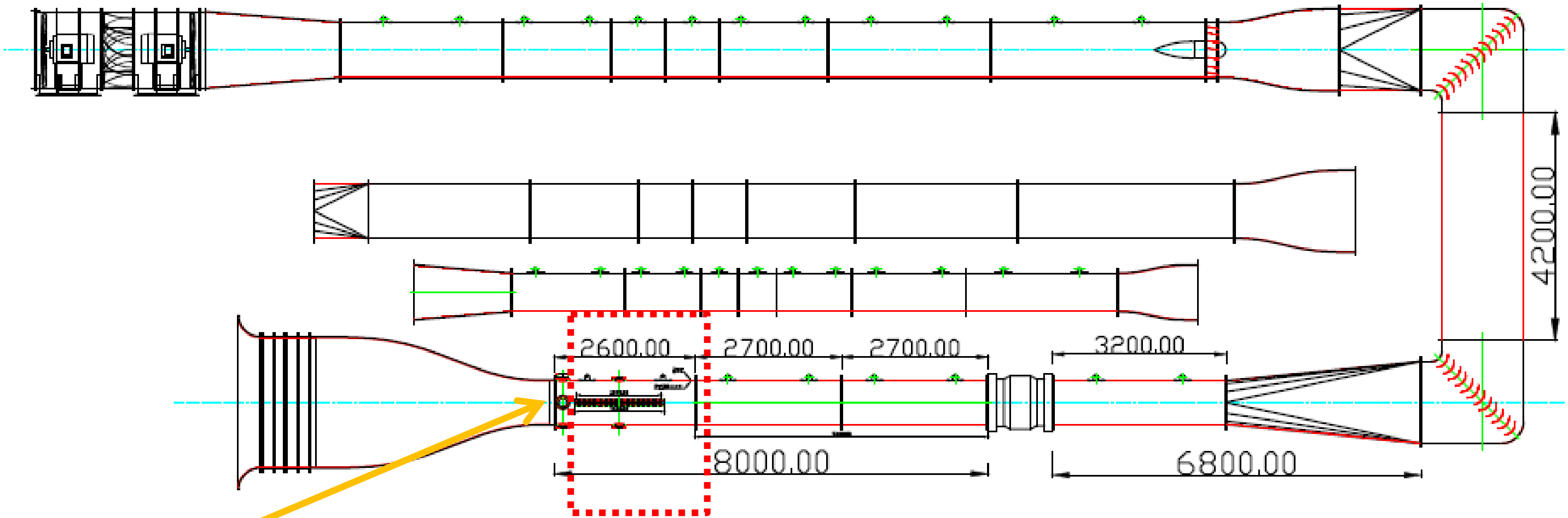






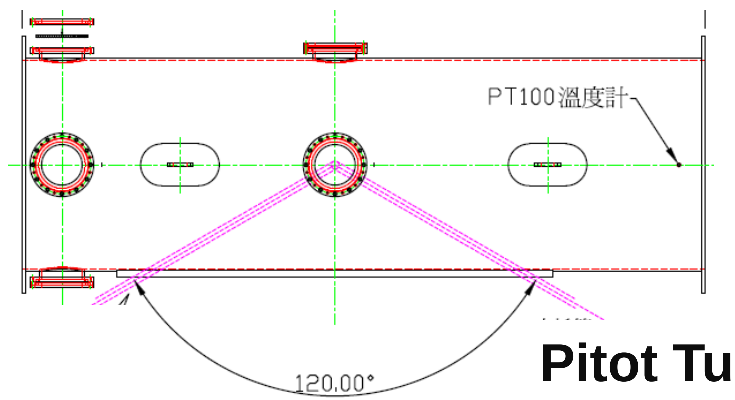


Pitot Tube Calibration Section

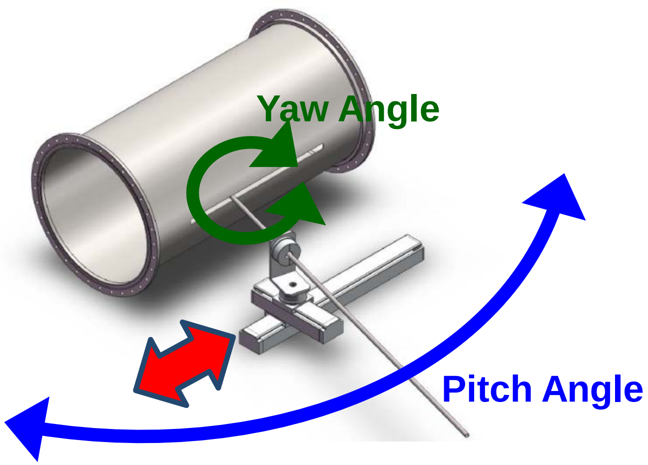


Tubulence Generator

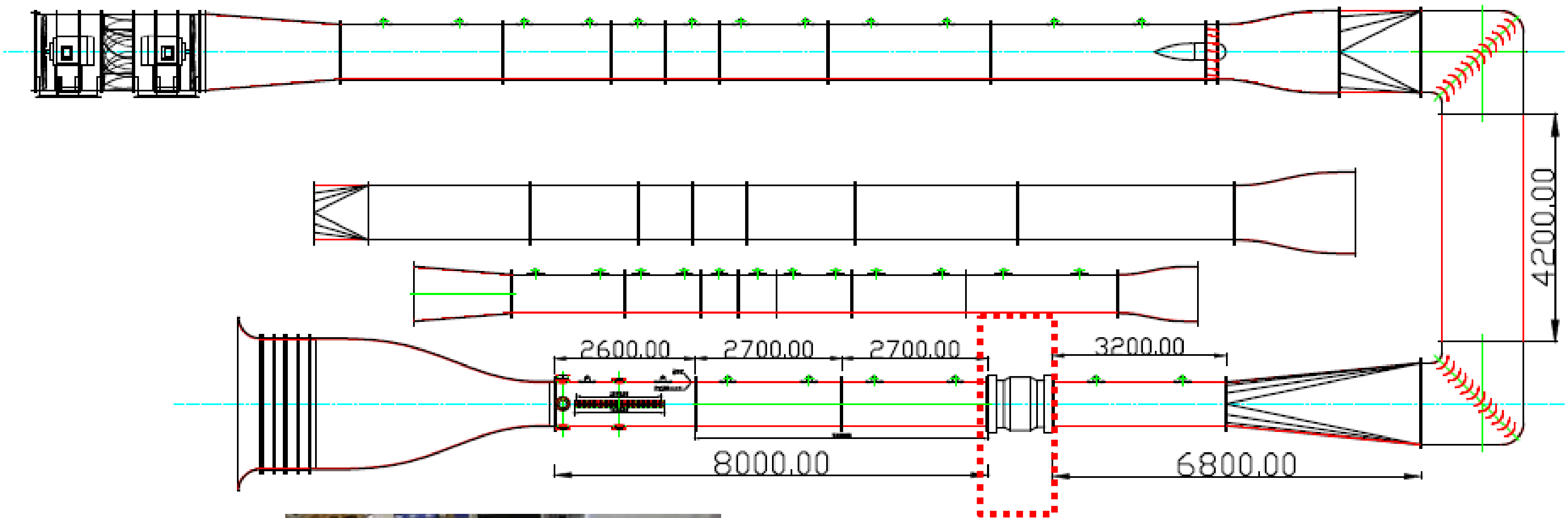
Pitot Tube Calibration Section



Pitot Tube

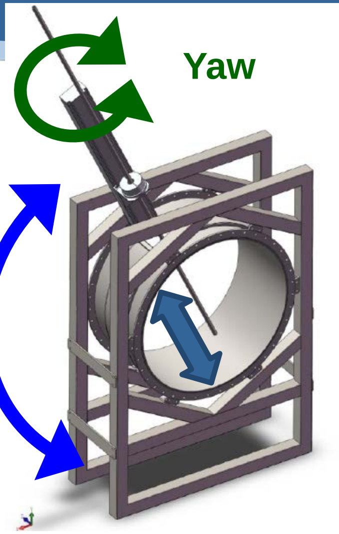


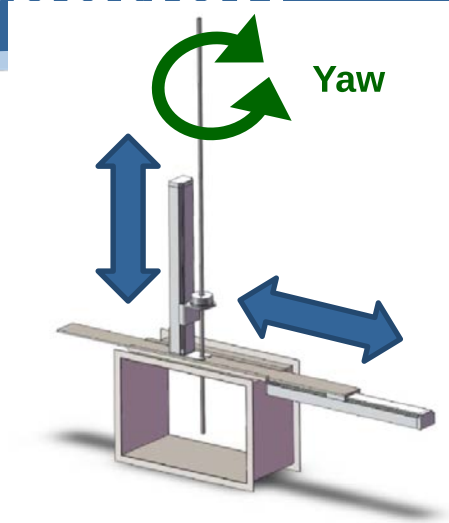
USM Working Standard

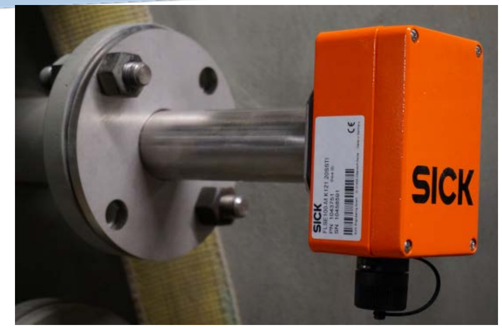


Working Standard:
DN800 8-Path Flowsic600
Ultrasonic Flowmeter

Test Section



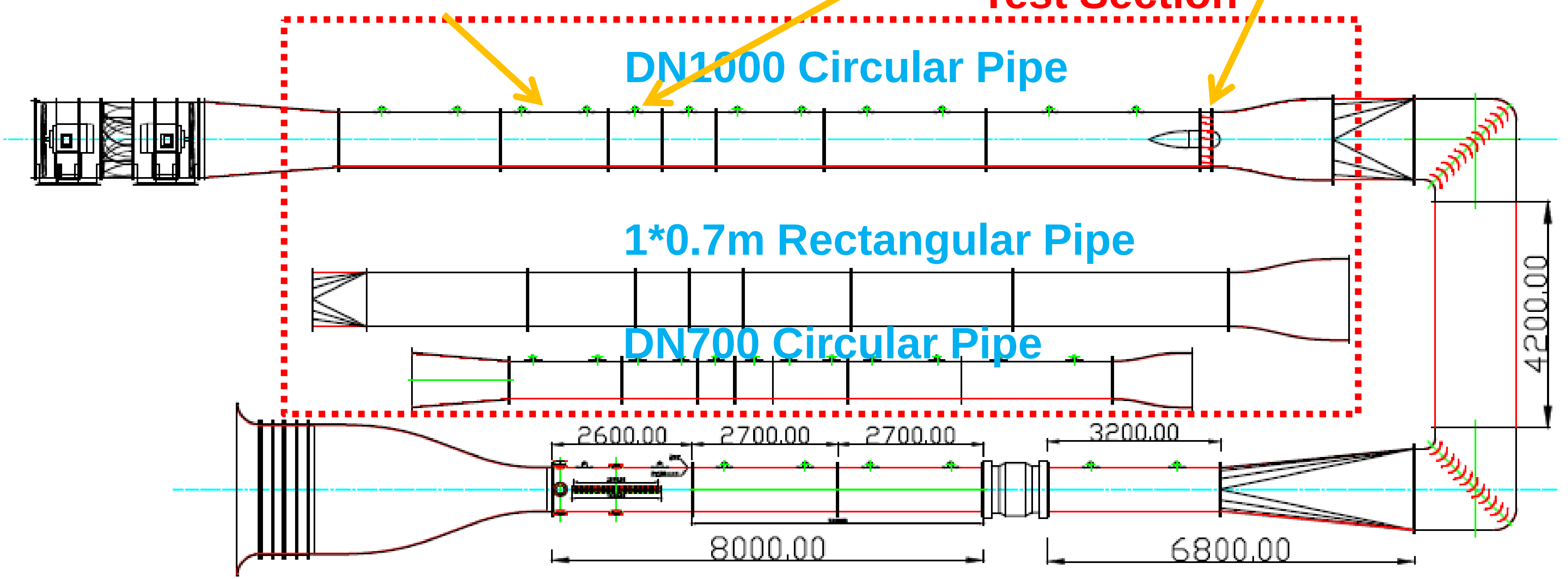




8-Path Flowsic100
Ultrasonic Flowmeter

Swirl & Turbulance
Generator

Pitot Tube



Completion Time: November 2015

Thank you for your attention

zhangliang@nim.ac.cn