Turbulent Inflow Profile for Numerical Wind Tunnel

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- Wind Tunnel Test
  - Measurement of Hotwire
  - Expose Category
  - Characteristic of Velocity with expose

- Synthetic Inflow
  - Wind Profile Code for Architecture
  - Inflow Generation
  - Computational Results

- Remark

Why Numerical Wind Tunnel?

- Wind Tunnel Test and Code (KBC 2009)
  - Subject of wind tunnel test

[Wind vibration architecture (AR over 3.5)]

[Unique roof and cladding]

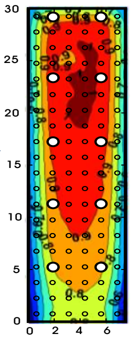
[Valley wind effect]

[Adjacent effect architecture (within 10D of architecture)]

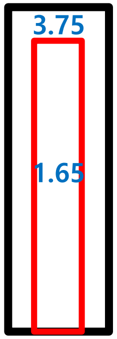
[Unique design (difficult to apply code)]

  - Korean building code (KBC 2009/2013)

Wind Exp.

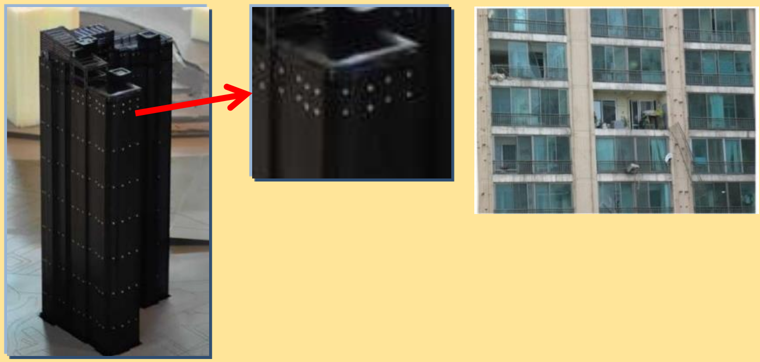


Exp. data



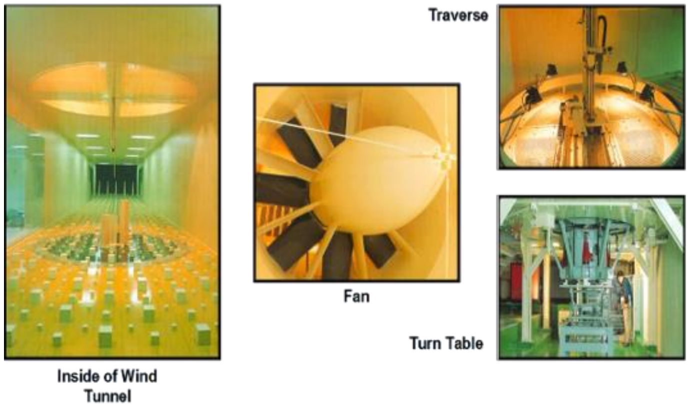
Code

Limitation of experiment and Real problem



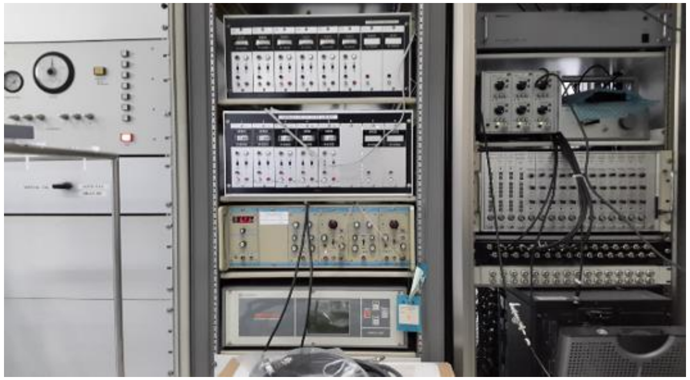
Wind Tunnel Test

- Daewoo E&C Facility Summary
  - Wind Tunnel Specification
    - Closed-circuit wind tunnel
    - Test section: 3m×2m
    - Max wind speed: 30m/s
    - Turbulent Intensity: 0.5%



[Wind Tunnel Components]

  - Measurement Specification
    - Multi-channel pressure array module
      - Red Hawk Ltd. 512 channel
      - 16bit ADC
      - Sampling rate: 400Hz

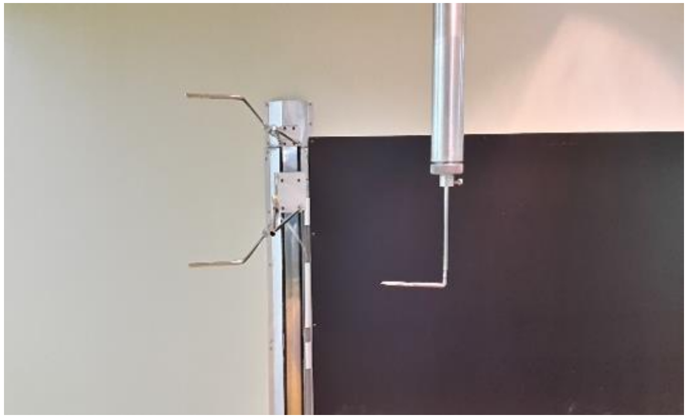


[Measurement Deck]

Wind Tunnel Test

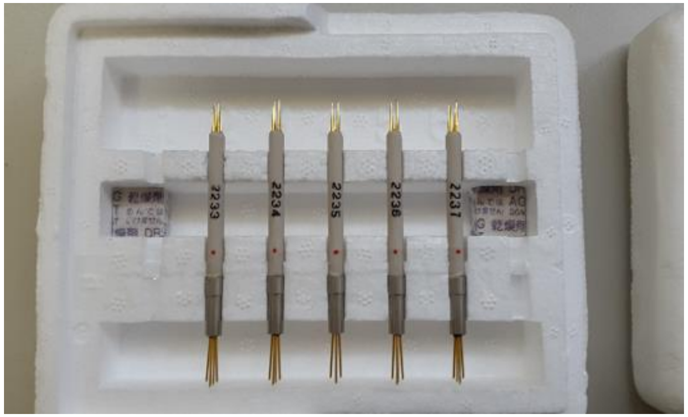
- Measurement Layout

[Upper Traverse Rod & Pitot]



[Upper Traverse Rod & Pitot]

  - Hotwire probe
    - Kanomax Inc. Model 0252R-T5, x-type
    - Resistance: 5.74Ω, Temp.: 150°C
- Measurement
  - 10cm interval from floor to 1m
  - Sampling rate 400Hz, during 60sec
  - Measure hotwire and pitot signals

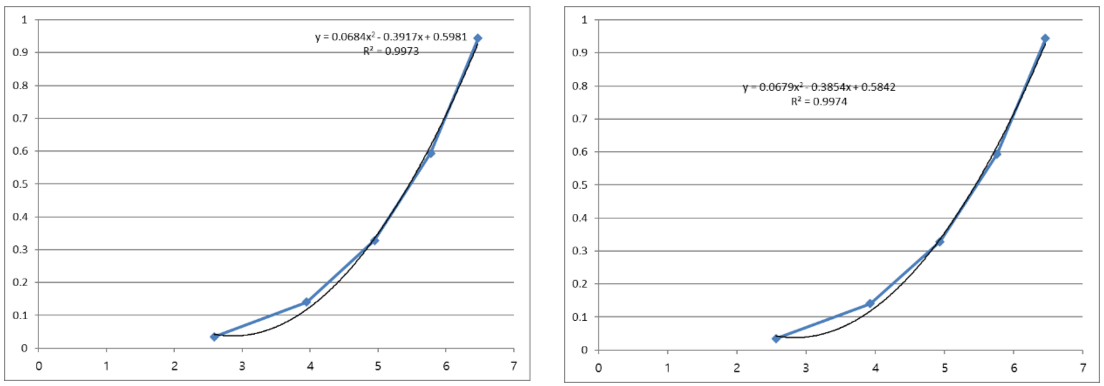


[Hotwire]

Wind Tunnel Test

RPM	ch1	ch2	Pitot	Pitot U
100	2.58929	2.565859	0.034625	2.353714
200	3.949537	3.923866	0.140403	4.739667
300	4.948932	4.931013	0.32777	7.241768
400	5.776872	5.756702	0.593191	9.742208
500	6.472368	6.458335	0.943504	12.28661

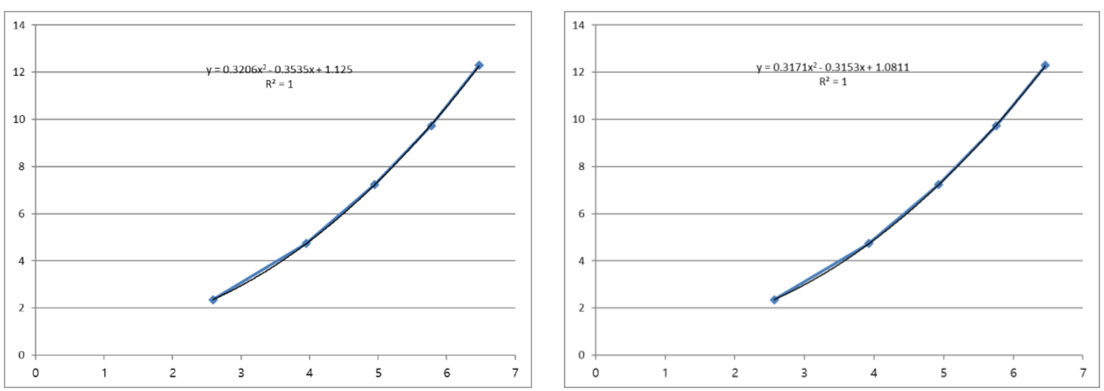
- Hotwire Correction
  - Pitot conversion wind speed
    - $U_{pitot} = 4\sqrt{pitot \times 10}$ [m/s]



[Hotwire-pitot signal correction]

Ch1-pitot signal
$y = 0.0684x^2 - 0.3917x + 0.5981; R^2 = 0.9973$

Ch2-pitot signal
$y = 0.0679x^2 - 0.3854x + 0.5842; R^2 = 0.9974$



[Hotwire-pitot wind speed through RPM]

Ch1-pitot wind speed
$y_{ch1} = 0.3206x^2 - 0.3535x + 1.125; R^2 = 1$

Ch2-pitot wind speed
$y_{ch2} = 0.3171x^2 - 0.3153x + 1.0811; R^2 = 1$

Velocity component
$u = \frac{1}{2}(y_{ch1} + y_{ch2}),\ w = \frac{1}{2}(y_{ch1} - y_{ch2})$

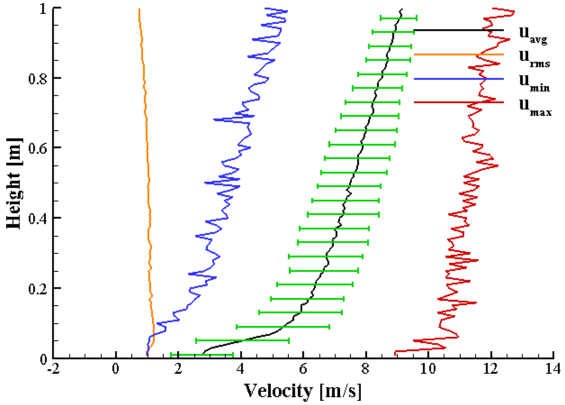
Wind Tunnel Test

- Expose A

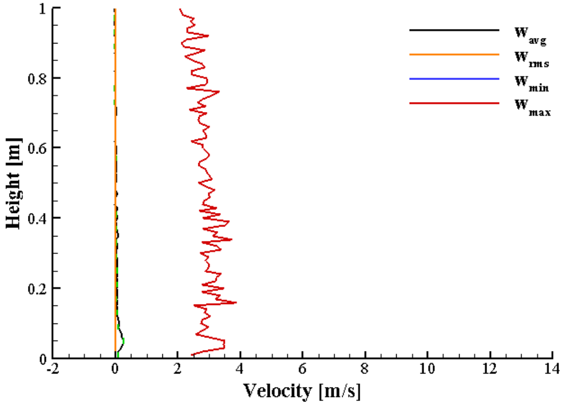
[Expose A Block Layout]

To close large high rise building over 10 stories at central urban area

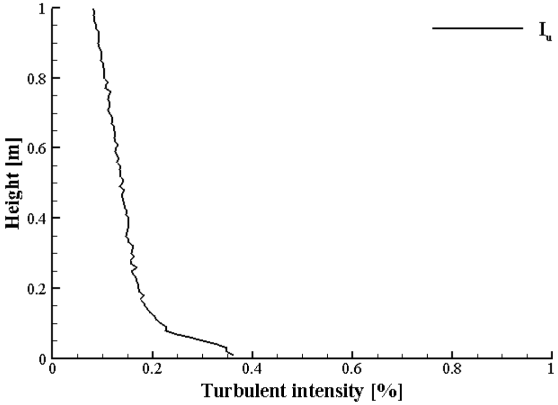
Wind speed
Avg. : 9.159 m/s at 1m
RMS_{avg} *: 1.089 m/s*
Max_{avg} *: 11.193 m/s*
Min_{avg} *: 3.316 m/s*



[U Velocity]



[W Velocity]



[Turbulent Intensity]

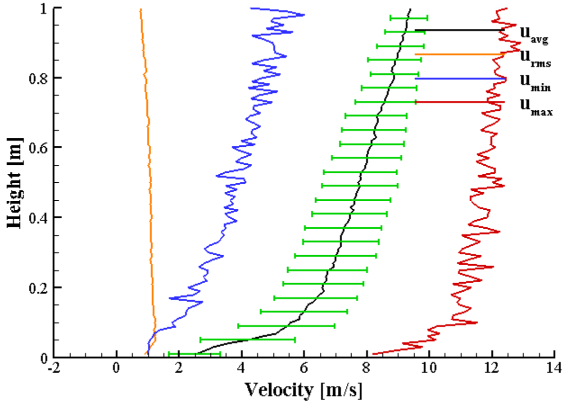
Wind Tunnel Test

- Expose B

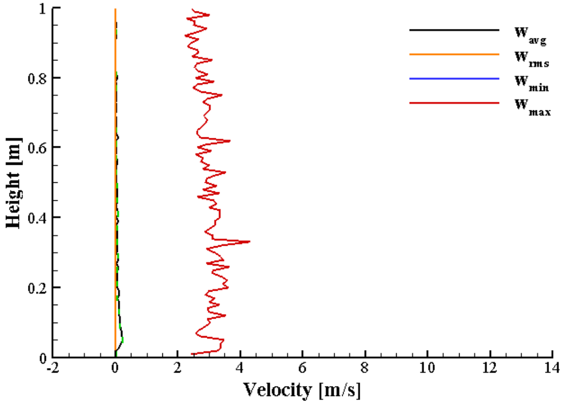
[Expose B Block Layout]

To close 3.5m height single-family dwelling area
To scatter medium rise building area

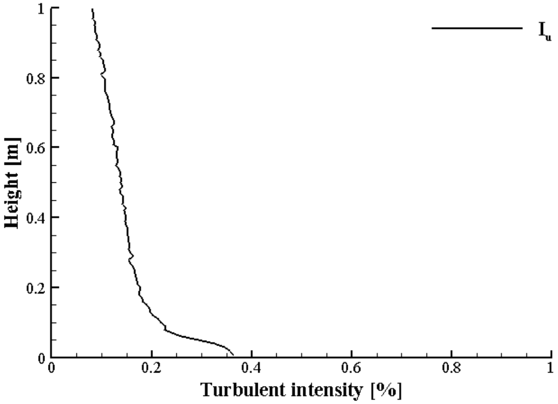
Wind speed
Avg. : 9.402 m/s at 1m
RMS_{avg} *: 1.195 m/s*
Max_{avg} *: 10.965 m/s*
Min_{avg} *: 2.744 m/s*



[U Velocity]



[W Velocity]



[Turbulent Intensity]

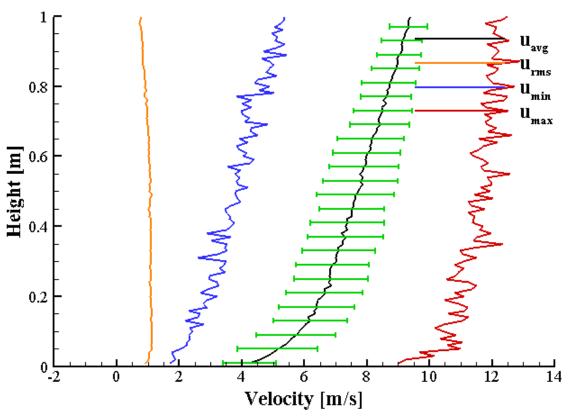
Wind Tunnel Test

- Expose C

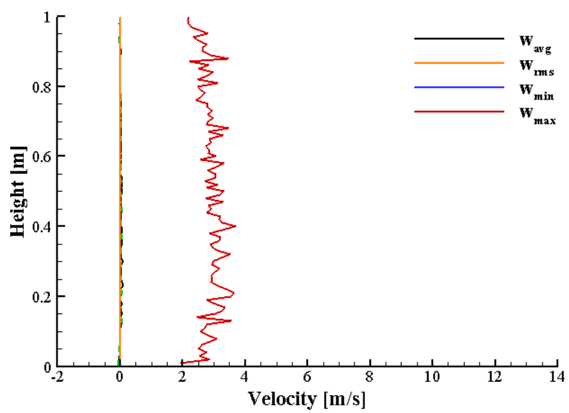
[Expose C Block Layout]

To scatter 1.5~10m height obstacle area
To scatter low rise building area

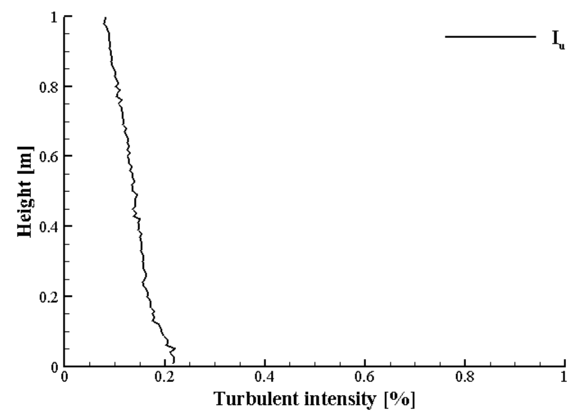
Wind speed
Avg. : 9.385 m/s at 1m
RMS_{avg} *: 1.077 m/s*
Max_{avg} *: 11.266 m/s*
Min_{avg} *: 3.356 m/s*



[U Velocity]



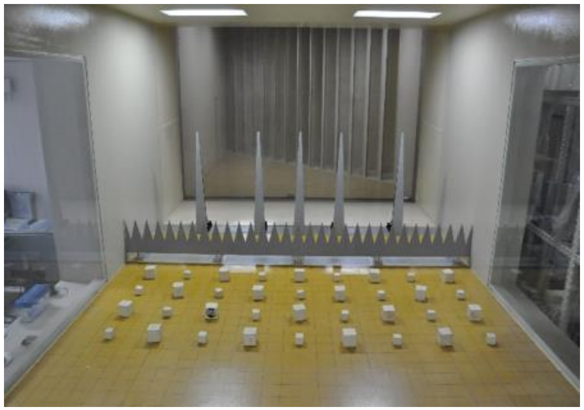
[W Velocity]



[Turbulent Intensity]

Wind Tunnel Test

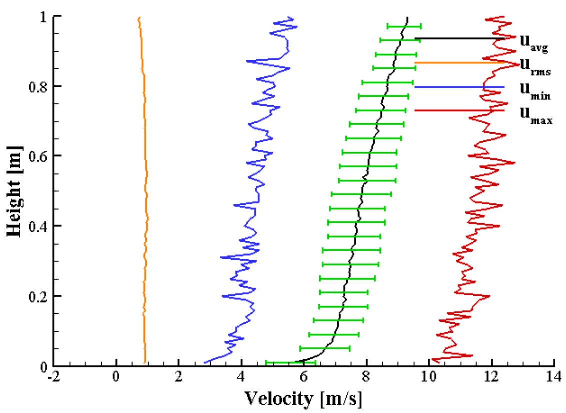
- Expose D



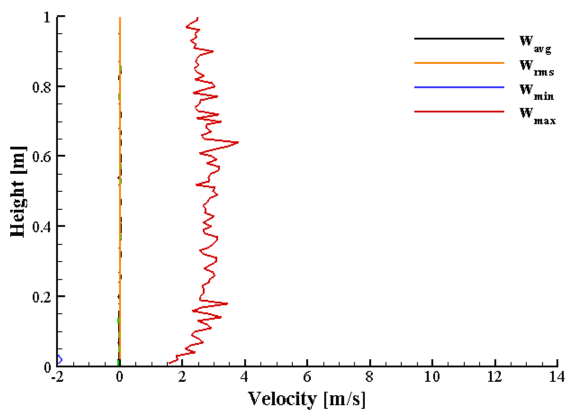
[Expose D Block Layout]

Unobstacle areas and water surface, grassland, airport
Average height 1.5m below
Obstacle area

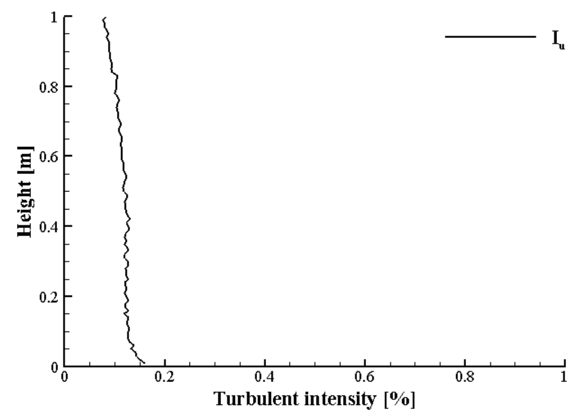
Wind speed
Avg. : 9.283 m/s at 1m
RMS_{avg} *: 0.905 m/s*
Max_{avg} *: 11.404 m/s*
Min_{avg} *: 4.240 m/s*



[U Velocity]



[W Velocity]



[Turbulent Intensity]

Wind Tunnel Test

- Wind Tunnel Test
  - KBC 2009 expose categories tested

	Velocity [m/s]			
Expose	A	B	C	D
Avg. at 1m	9.159	9.402	9.385	9.283
RMS	1.089	1.195	1.077	0.905
Umax	11.193	10.965	11.266	11.404
Umin	3.316	2.744	3.356	4.240

  - W-direction velocity
    - 25% of average velocity
  - Building pressure test
    - 75×75×300 mm
    - Two types of contemporary apartment
    - Test bad model

Synthetic Inflow

- Velocity and Turbulence
  - KBC2009 flow profile and AIJ guidebook(2007)
    - Y. Tominaga, A. Mochida, R. Yoshie, H. Kataoka, T. Nozu, M. Yoshikawa, T. Shirasawa, "AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 96. pp. 1749–1761, 2008
    - $U(z) = U_{ref}\left(\frac{z}{z_{ref}}\right)^{\alpha}$
    - $I_u(z) = 0.1\left(\frac{z}{z_g}\right)^{-\alpha-0.05}$, $I_u = \frac{u'}{\bar{u}}$
    - $k(z) = (I_u(z)U(z))^2$
    - $\epsilon(z) = \sqrt{C_\mu}k(z)\frac{U_{ref}}{z_{ref}}\alpha\left(\frac{z}{z_{ref}}\right)^{(\alpha-1)}$
  - Fluctuation part
    - Characteristics of atmospheric turbulence near the ground part II: single point data for strong winds (neutral atmosphere), ESDU 85020, ISSN 0143-2702, 2001
    - $\frac{\sigma_v}{\sigma_u} = 1 - 0.22\cos^4\left(\frac{\pi}{2}\frac{z}{z_{ref}}\right)$
    - $\frac{\sigma_w}{\sigma_u} = 1 - 0.45\cos^4\left(\frac{\pi}{2}\frac{z}{z_{ref}}\right)$
    - $\sigma_v = 0.5\sigma_u, \sigma_w = 0.35\sigma_u$

Synthetic Inflow

- Inflow Condition Generation Methods
  - LES, pre-cursor DNS for channel flow
    - Limited low Reynolds, difficult rescale DNS fluctuation in high Reynolds
  - Re-scale method
    - Use downward resolved fluctuation for inlet condition with rescale
  - Vortex method
    - Partially synthetic fluctuation
    - Eddy is defined geometrical function

- Inlet Inflow in OpenFOAM
  - src/turbulentModels/incompressible/RAS/derivedFvPatch
  - Logarithm velocity profile
    - atmBoundaryLayer
    - atmBoundaryLayerInletEpsilon
    - atmBoundaryLayerInletK
    - atmBoundaryLayerInletVelocity

Synthetic Inflow

- GroovyBC
  - Swak4foam
  - Easy to implement on BC

```
ABLvariables ("Uref=9.159;"
              "Href=1.0;"
              "alpha=0.23;"
              "flucx=1.0;"
              "flucy=0.5;"
              "flucz=0.35;"
              "Ux=Uref*pow((pos().z/Href),alpha);"
              "Ti=0.1*pow((pos().z/Href),-alpha-0.05);"
              "ux=flucx*Ux*Ti;"
              "uy=flucy*ux;"
              "uz=flucz*ux;"
              "Uy=0.25*flucx*Ux;"
              "Uz=0.5*Uy;"
              "Utx=Ux+randNormal()*ux;"
              "Uty=(Uy+uy)*randNormal();"
              "Utz=(Uz+uz)*randNormal();"
             );

ABLTkvariables ("Uref=9.159;"
                "Href=1.0;"
                "alpha=0.23;"
                "flucx=1.0;"
                "Ux=Uref*pow((pos().z/Href),alpha);"
                "Ti=0.1*pow((pos().z/Href),-alpha-0.05);"
                "ux=flucx*Ux*Ti;"
                "Utx=Ux+randNormal()*ux;"
                "Tk=pow((Utx*Ti),2);"
               );

ABLTevariables ("Uref=9.159;"
                "Href=1.0;"
                "alpha=0.23;"
                "flucx=1.0;"
                "Cmu=0.0845;"
                "Ux=Uref*pow((pos().z/Href),alpha);"
                "Ti=0.1*pow((pos().z/Href),-alpha-0.05);"
                "ux=flucx*Ux*Ti;"
                "Utx=Ux+randNormal()*ux;"
                "Tk=pow((Utx*Ti),2);"
                "Prefac=sqrt(Cmu)*Tk*Uref/Href*alpha;"
                "Te=Prefac*pow((pos().z/Href),alpha-1.0);"
               );
```

[Inlet Condition]

Power law velocity profile

$$U(z) = U_{ref}\left(\frac{z}{z_{ref}}\right)^{\alpha}$$

Turbulent intensity profile

$$I_u(z) = 0.1\left(\frac{z}{z_g}\right)^{-\alpha-0.05}$$

Fluctuation part

$$\sigma_v = 0.5\sigma_u, \sigma_w = 0.35\sigma_u$$

Turbulent kinetic energy profile

$$k(z) = (I_u(z)U(z))^2$$

Turbulent dissipation profile

$$\epsilon(z) = \sqrt{C_\mu}k(z)\frac{U_{ref}}{z_{ref}}\alpha\left(\frac{z}{z_{ref}}\right)^{(\alpha-1)}$$

Synthetic Inflow

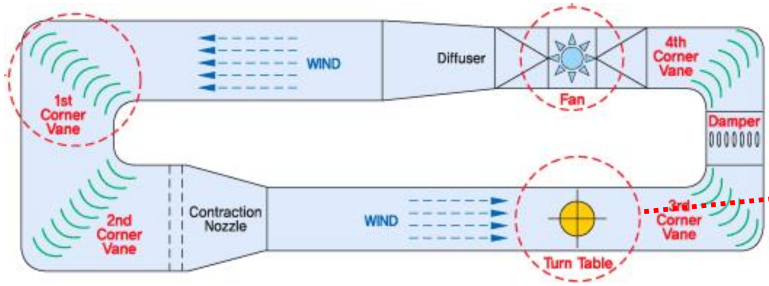
- Surface Roughness
  - Expose Categories A, B, C, D
    - Need to correct different roughness height
    - O.Kruger, C.Schrodinger, A.Lengwinant, and C.O.Paschereit, “Numerical Modeling and Validation of the wind flow over the lake wannsee,” 11th world congress on computational mechanics, Barcelona, Spain, 2014.
    - B.Blocken, T.Stathopoulos, and J.Carmeliet, ”CFD simulation of the atmospheric boundary layer: wall function problems, atmospheric environment, vol. 41, No. 2, pp. 238-252, 2007.
      - Recommended value
        - » $C_s = 0.327$
        - » $K_s = 30z_0$
        - » $E = 9.793$
  - nutKRoughWallFunction
    - $\frac{u_p}{u^*} = \frac{1}{\kappa}\ln\left(\frac{Ez_p}{C_s k_s}\right),\ u^* = C_\mu^{1/4} k^{1/2}$

Expose	A	B	C	D
Cs	0.6	0.5	0.4	0.3
Ks(=30z0)	0.04125	0.05646	0.006723	0.00028125
E	9.793			

[Tuned Values of Roughness Constant from wind tunnel test]

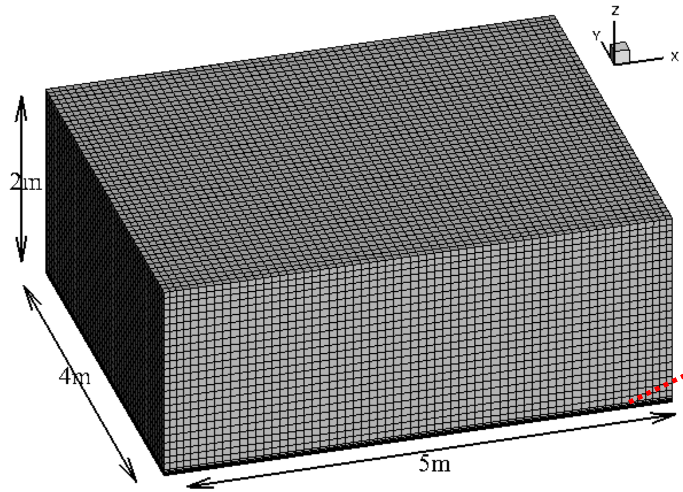
Synthetic Inflow

- Computational Setup
  - Wind tunnel modeling
    - Geometry: Salome
      - Length: -3~2m (=5m)
      - Width: -2~2m (=4m)
      - Height: 2m



[Computational Region]

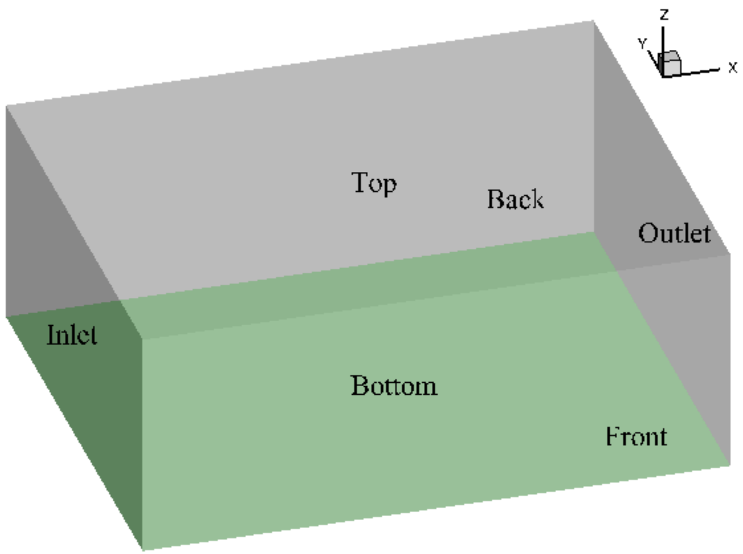
- Mesh generator: cfMesh
  - maxCellSize: 0.08m (probe location each 0.1m in wind tunnel test)
  - Boundary layer 11 on bottom
  - Target y+: 100 (=0.005m)



[Mesh Configuration]

Synthetic Inflow

- Computational Setup
  - Boundary Condition
    - Inlet: turbulent velocity inlet (groovyBC)
    - Outlet: extrapolation (zeroGradient)
    - Bottom: non-slip wall
    - Top: symmetry
    - Front and Back: extrapolation (zeroGradient)



[Boundary Condition]

Expose	A	B	C	D
Velocity	9.159	9.402	9.385	9.283
Pressure	0	0	0	0
Turb. K	1.258	1.326	1.321	1.293
Turb. e	0.116	0.125	0.124	0.121
NuTilda	0.116	0.125	0.124	0.121
R	1.445	1.483	1.481	1.465
	1.161	1.192	1.189	1.177
	0.755	0.776	0.774	0.766

Turbulent kinetic energy

$$K = 1.5(IU)^2$$

Turbulent dissipation

$\epsilon = C_\mu 0.75 \frac{K^{1.5}}{L}$, *L=2m (turntable size)*

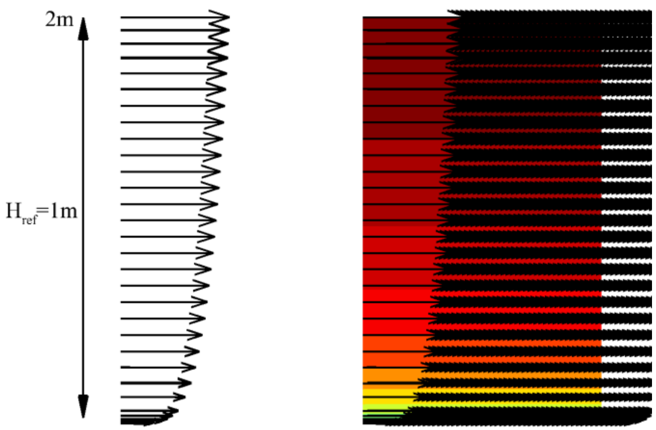
Reynolds stress tensor

$R_x = 2.39u^*,\ R_y = 1.92u^*,\ R_z = 1.25u^*$

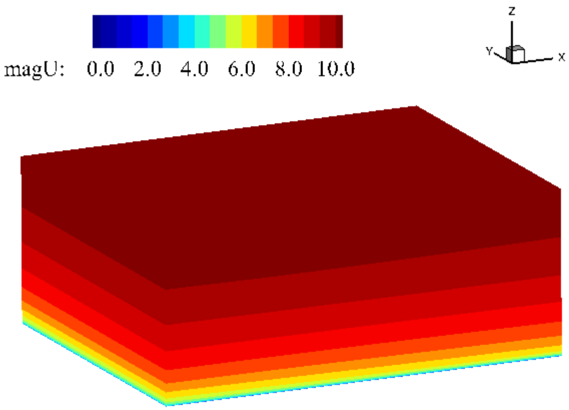
$$u^* = C_\mu^{0.25} K^{0.5}$$

Synthetic Inflow

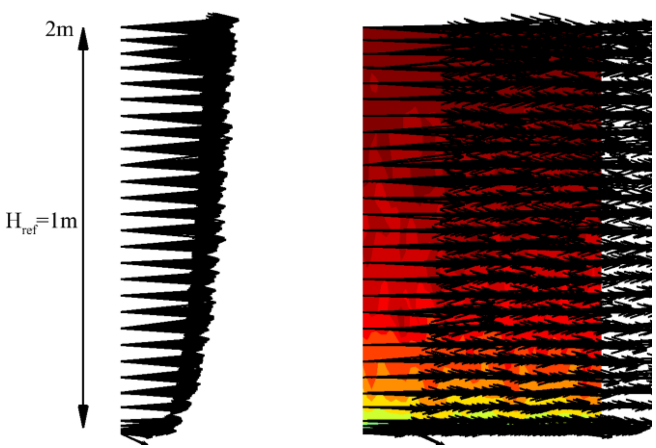
- Expose C Flow Field



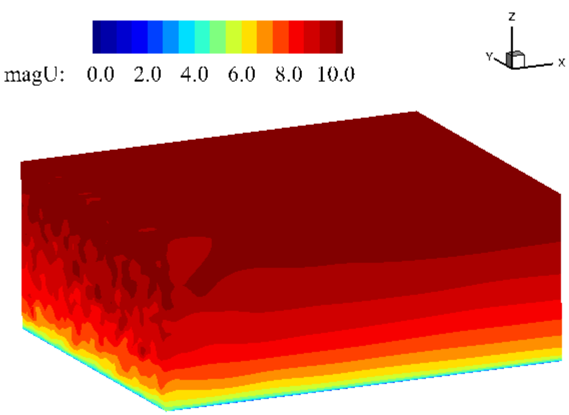
[Inlet Velocity Vector, Expose C, k-e model, steady]



[Expose C, k-e model, steady]



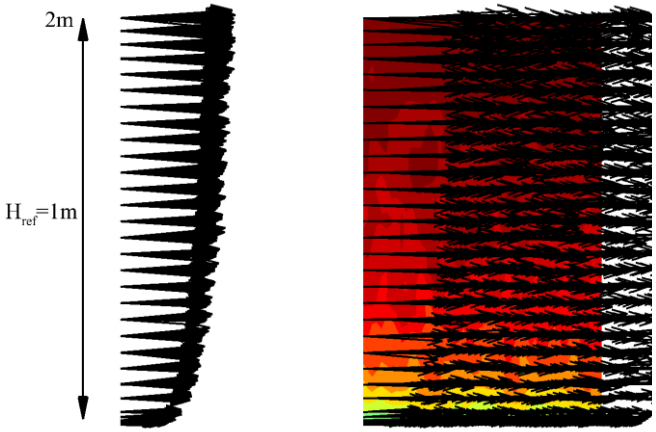
[Inlet Velocity Vector, Expose C, k-e model, unsteady]



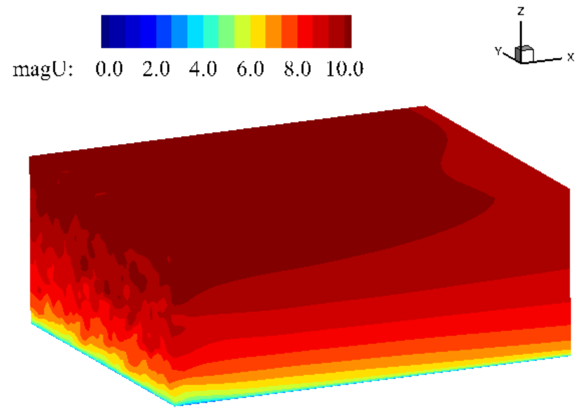
[Expose C, k-e model, unsteady]

Synthetic Inflow

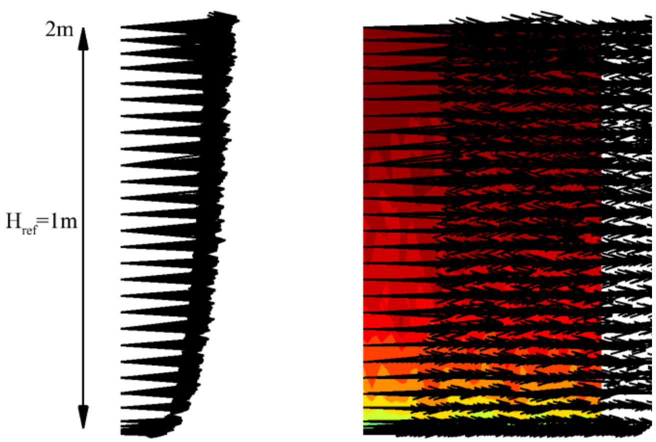
- Expose C Flow Field



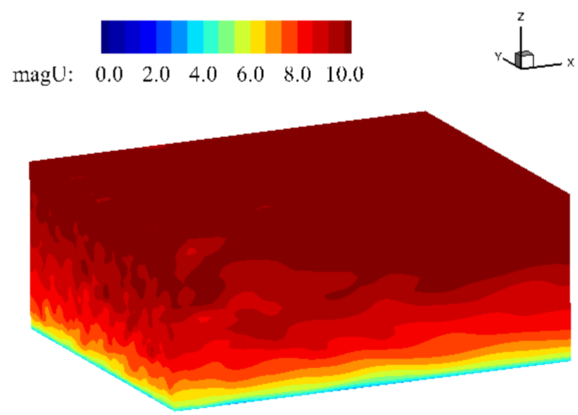
[Inlet Velocity Vector, Expose C, RSTM model, unsteady]



[Expose C, RSTM model, unsteady]



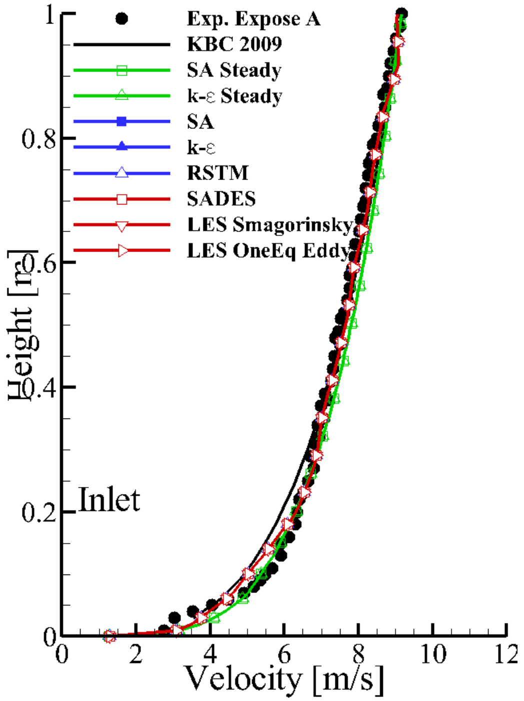
[Inlet Velocity Vector, Expose C, LES Smagorinsky model, unsteady]



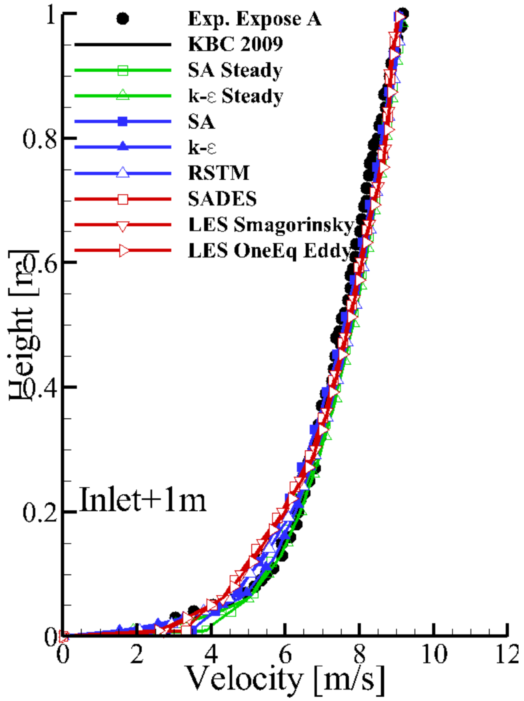
[Expose C, LES Smagorinsky, unsteady]

Synthetic Inflow

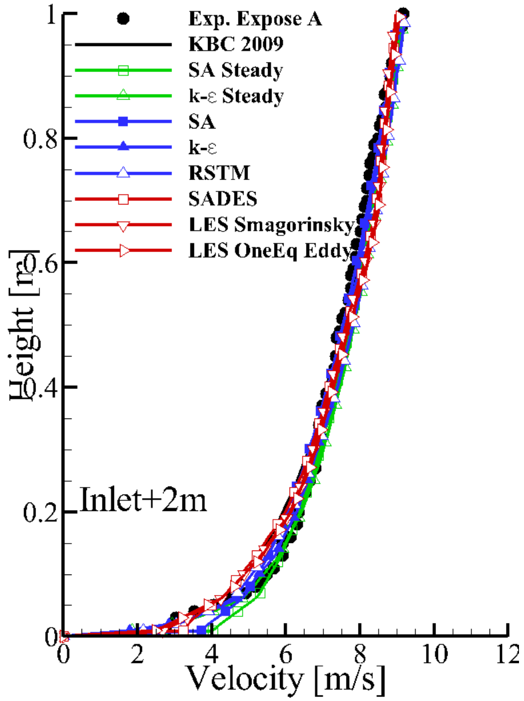
- Expose A



[Inlet Velocity Profile]



[Inlet+1m Velocity Profile]

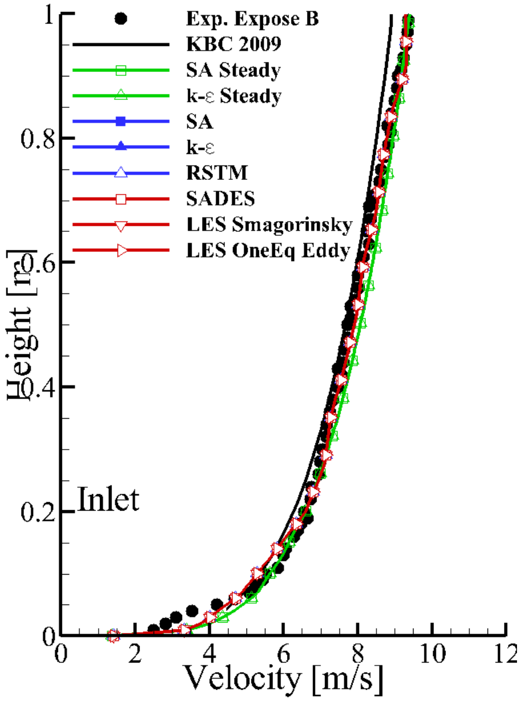


[Inlet+2m Velocity Profile]

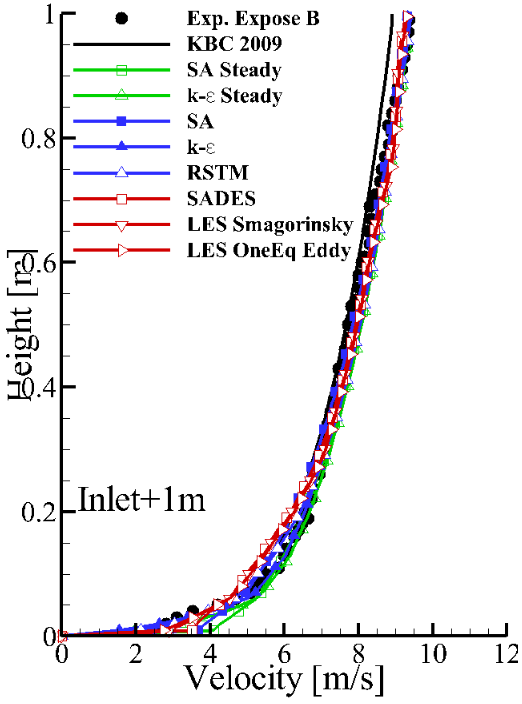
- Turntable inlet located 2m from Inlet BC
  - Two equation k-e families is similar to experiment data
  - One equation SA is not good agreement near wall
  - LES results show good agreement of KBC 2009 expose A

Synthetic Inflow

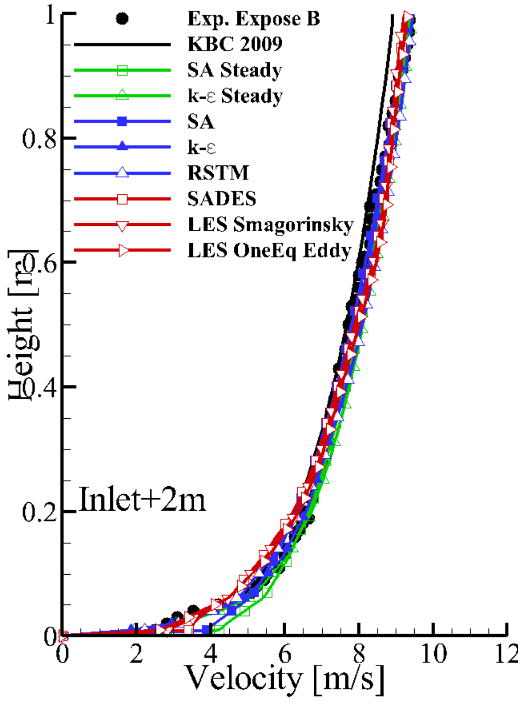
- Expose B



[Inlet Velocity Profile]



[Inlet+1m Velocity Profile]

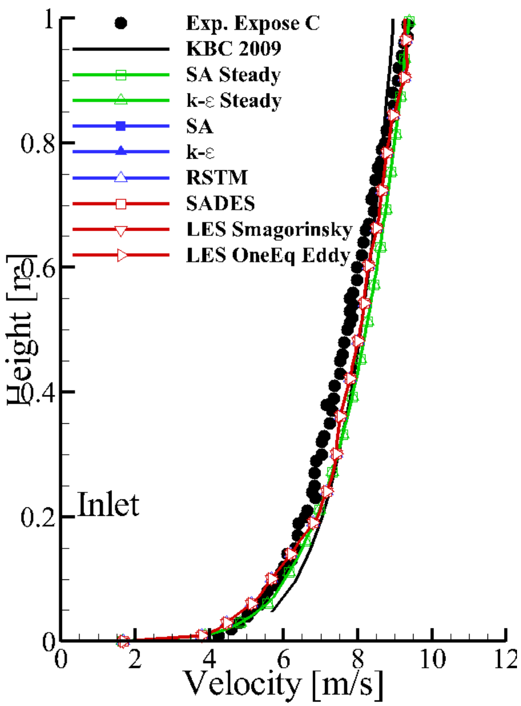


[Inlet+2m Velocity Profile]

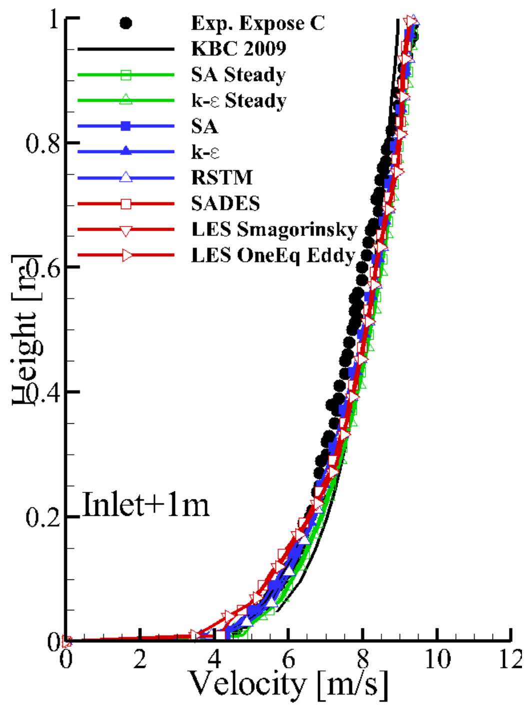
- Turntable inlet located 2m from Inlet BC
  - Two equation k-e families is similar to experiment data
  - One equation SA is not good agreement near wall
  - LES results show good agreement of KBC 2009 expose B and Exp

Synthetic Inflow

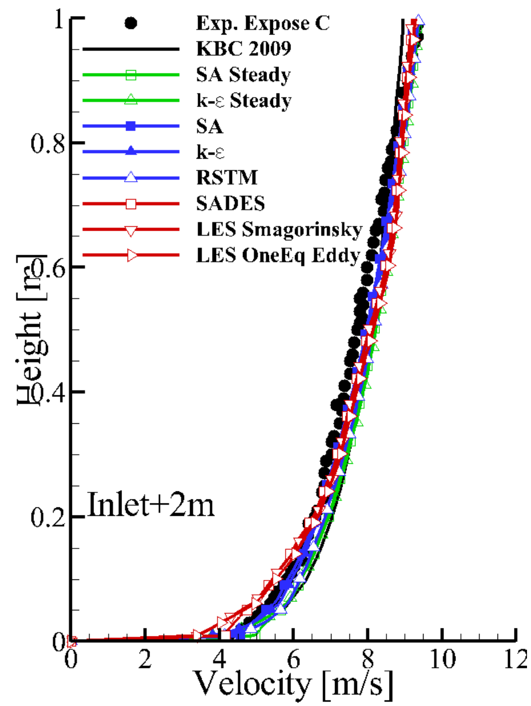
- Expose C



[Inlet Velocity Profile]



[Inlet+1m Velocity Profile]

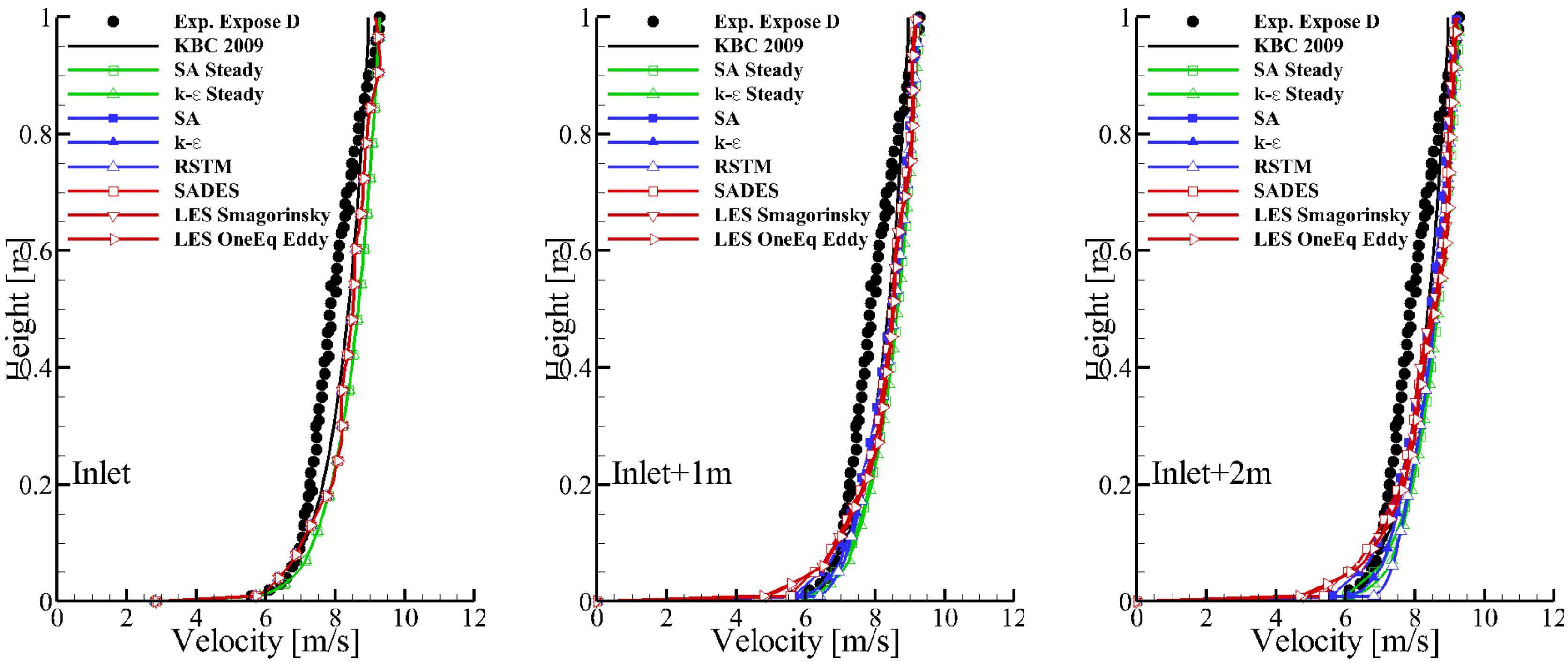


[Inlet+2m Velocity Profile]

- Turntable inlet located 2m from Inlet BC
  - One equation SA is similar to experiment data near wall
  - Two equation k-e and LES results between Exp. and KBC 2009 expose C

Synthetic Inflow

- Expose D



[Inlet Velocity Profile] [Inlet+1m Velocity Profile] [Inlet+2m Velocity Profile]

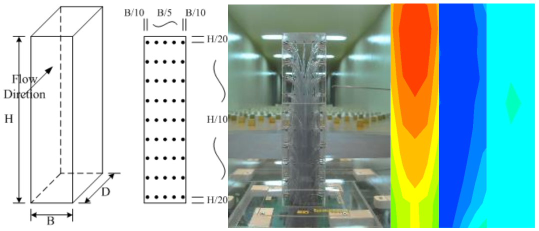
- Turntable inlet located 2m from Inlet BC
  - One equation SA is similar to experiment data near wall
  - Two equation k-e is more stiff gradient near wall
  - All models follow a KBC 2009 expose D profile

Remark

- Inlet conditions
  - Korean Building Code 2009
  - Fluctuation part of velocity profile at inlet
    - Randomized velocity with space

- From the results of simulation with turbulent model
  - All most models are good agreement to KBC 2009 and Exp.
    - Fluctuation characteristic of flow field
      - LES
        - » Velocity components do not decay in simulation field
      - RANS
        - » Inlet velocity fluctuation is rapidly decay
        - » Downward flow is similar to steady flow result

- Next works
  - Pressure test on the structure
    - 75 cube (wind tunnel validation case)
    - Two types of apartment pressure test with exp.



[Bluff Body Exp. and CFD]

Thank you for your attention