Validation of CFD Software Packages in Modeling Pollutant Dispersion

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HKUST

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Outline

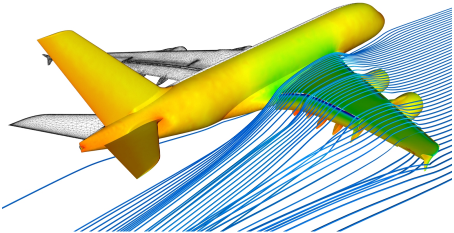
Outline

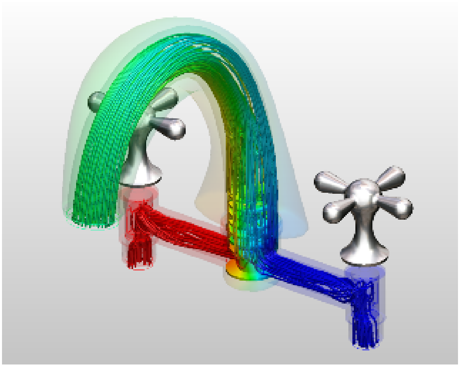
A globally recognized engineering firm that offers technical and management solutions, specialising in construction, engineering, environmental services, etc.

Air Pollution

[3]

Computational Fluid Dynamics (CFD)





[1] [4]

The Navier-Stokes Equations (Incompressible)

- Equation of continuity:

$$\frac{\partial u_i}{\partial x_i} = 0$$

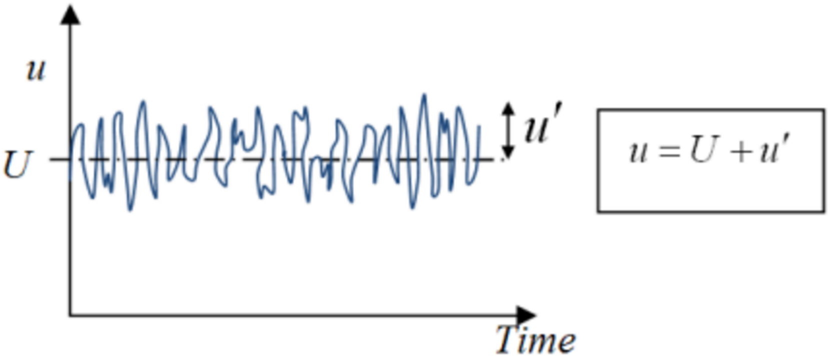
- Equation of momentum:

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(2\mu s_{ji}) + p g_i,$$

where $s_{ji} = \frac{1}{2}(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i})$.

Reynolds Averaging

Mean component + Fluctuating component



[5]

Reynolds Averaging Cont.

For a generic variable $u(\mathbf{x}, t)$, we have

$$u(\mathbf{x}, t) = U(\mathbf{x}) + u'(\mathbf{x}, t),$$

where Reynolds time-averaging is defined as

$$U(\mathbf{x}) =: \bar{u}(\mathbf{x}, t) = \lim_{\tau \to \infty} \frac{1}{\tau} \int_t^{t+\tau} u(\mathbf{x}, t) \, \mathrm{d}t.$$

[2]

The Reynolds-Averaged Navier-Stokes (RANS) Equations

- Equation of continuity:

$$\frac{\partial U_i}{\partial x_i} = \frac{\partial u_i'}{\partial x_i} = 0$$

- Equation of momentum:

$$\frac{\partial}{\partial t}(\rho U_i) + U_j \frac{\partial}{\partial x_j}(\rho U_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(2\rho\nu \overline{S_{ji}}) - \frac{\partial}{\partial x_j}(\rho \overline{u_i' u_j'}),$$

where $S_{ji} = \frac{1}{2}(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i})$ is the mean strain rate tensor.

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Note: the nonlinear term $\rho\overline{u_i' u_j'}$ is called the Reynolds stress.

[2]

The Boussinesq Eddy Viscosity Assumption

For an incompressible flow, the Reynolds stress is modeled as

$$\rho\overline{u_i'u_j'} = \mu_t\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \frac{2}{3}k\rho\delta_{ij}.$$

The Boussinesq Eddy Viscosity Assumption

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The scalar property μ_t is called the eddy viscosity.

[2]

Generic Scalar Transport Equation

For a generic scalar variable ϕ, we have

$$\frac{\partial(\rho\phi)}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i \phi) = \frac{\partial}{\partial x_i}\left[\Gamma \frac{\partial \phi}{\partial x_i}\right] + S,$$

where S is the source term, and Γ is the diffusion coefficient.

Turbulence Model

The Realizable $k-\epsilon$ (RKE) Model:

$$\begin{cases} \frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho U_j k)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right) + \tau_{ij}\frac{\partial U_i}{\partial x_j} - \rho\epsilon \\ \frac{\partial(\rho\epsilon)}{\partial t} + \frac{\partial(\rho\epsilon U_j)}{\partial x_j} = \left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\nabla^2\epsilon + C_1 S\rho\epsilon - C_2\frac{\rho\epsilon^2}{k+\sqrt{\nu\epsilon}} \end{cases}$$

[6]

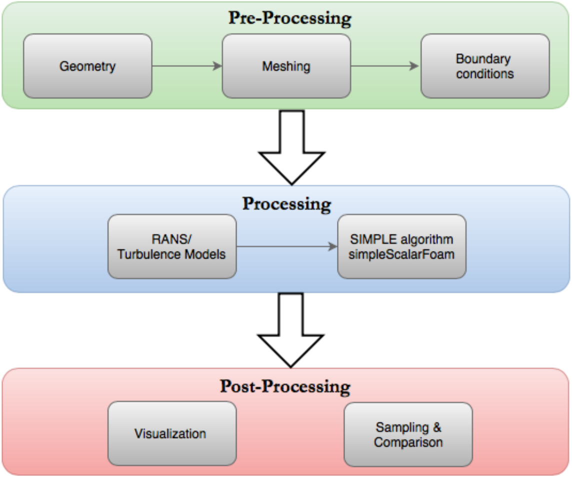
Mass Transport

$$\frac{\partial T}{\partial t} + \nabla \cdot (\vec{u}T) - \nabla^2 \left(\left(D_T + \frac{\mu_t}{Sc_t} \right) T \right) = R,$$

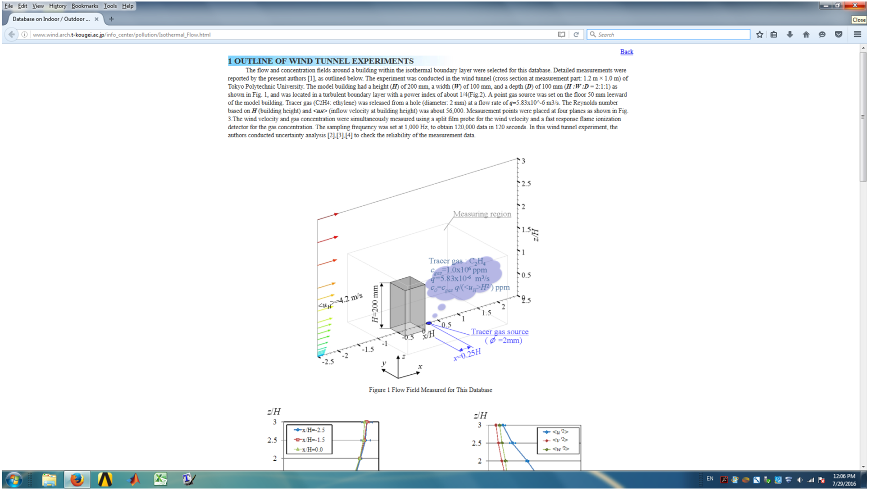
where R is the source term, D_T is the mass diffusivity, and Sc_t is the turbulent Schmidt number.

Outline

Setting Up the Model



Tokyo Polytechnic University (TPU) Wind Tunnel Experiment



Back

1 OUTLINE OF WIND TUNNEL EXPERIMENTS

The flow and concentration fields around a building within the isothermal boundary layer were selected for this database. Detailed measurements were reported by the present authors [1], as outlined below. The experiment was conducted in the wind tunnel (cross section at measurement part: 1.2 m × 1.0 m) of Tokyo Polytechnic University. The model building had a height (***H***) of 200 mm, a width (***W***) of 100 mm, and a depth (***D***) of 100 mm (***H*** **:*W*** **:*D*** = 2:1:1) as shown in Fig. 1, and was located in a turbulent boundary layer with a power index of about 1/4(Fig.2). A point gas source was set on the floor 50 mm leeward of the model building. Tracer gas (C2H4: ethylene) was released from a hole (diameter: 2 mm) at a flow rate of ***q***=5.83x10^-6 m3/s. The Reynolds number based on ***H*** (building height) and <*uH*> (inflow velocity at building height) was about 56,000. Measurement points were placed at four planes as shown in Fig. 3.The wind velocity and gas concentration were simultaneously measured using a split film probe for the wind velocity and a fast response flame ionization detector for the gas concentration. The sampling frequency was set at 1,000 Hz, to obtain 120,000 data in 120 seconds. In this wind tunnel experiment, the authors conducted uncertainty analysis [2],[3],[4] to check the reliability of the measurement data.

Figure 1 Flow Field Measured for This Database

[7]

Geometry

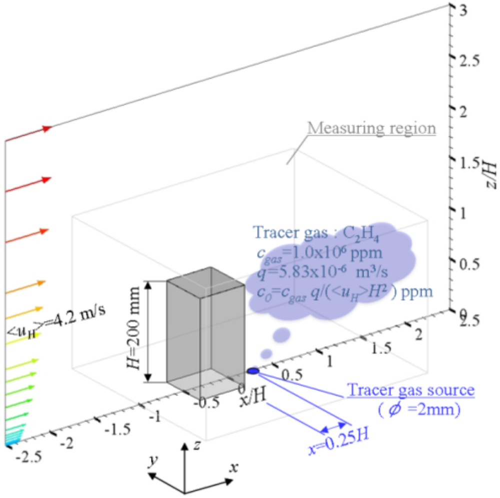
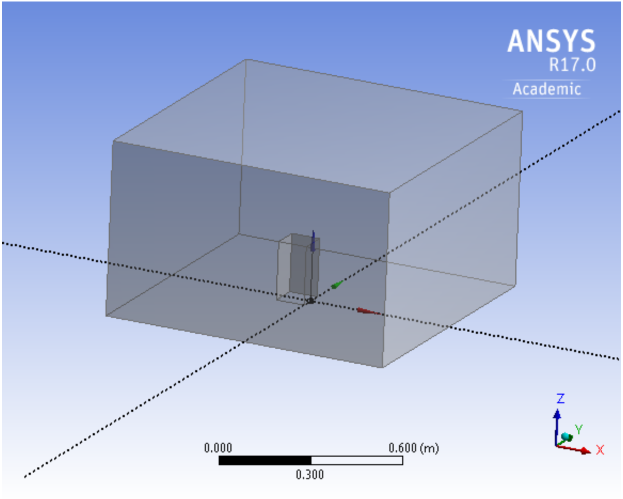


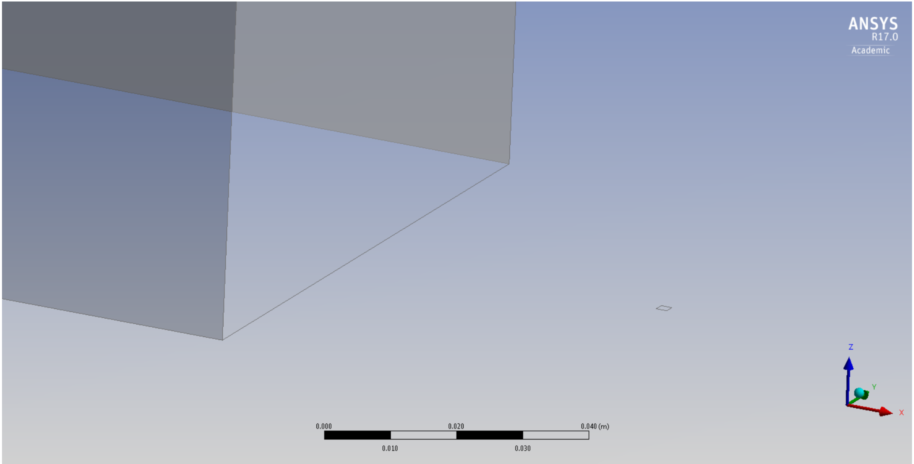
Figure 1 Flow Field Measured for This Database

[7]

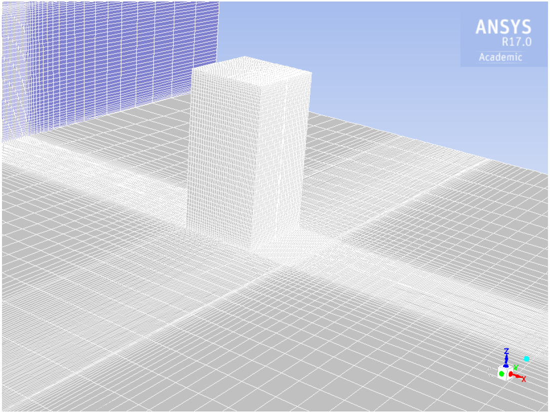
Geometry Cont.



Geometry Cont.



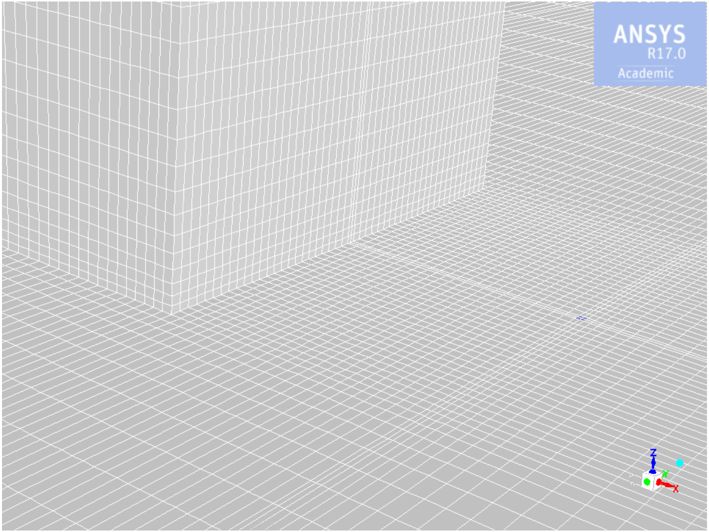
Meshing



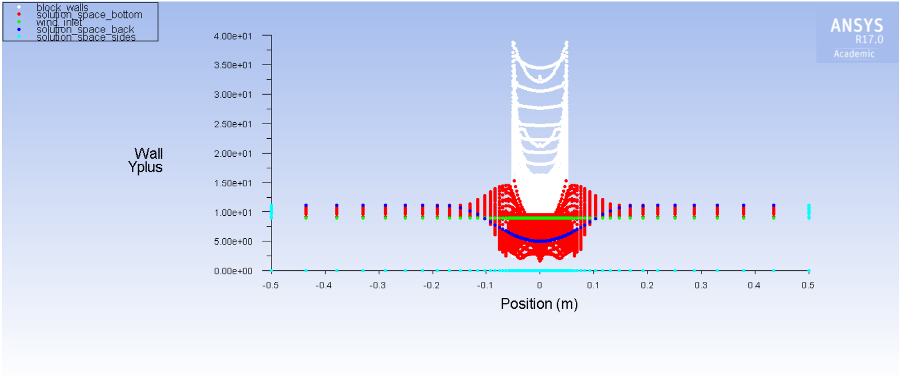
$$y^+ = \frac{y u_\tau}{\nu}$$

$$\frac{U}{u_*} = \frac{1}{\kappa} ln(y^+) + B$$

Meshing Cont.



Meshing Cont.



Boundary Conditions and Parameters

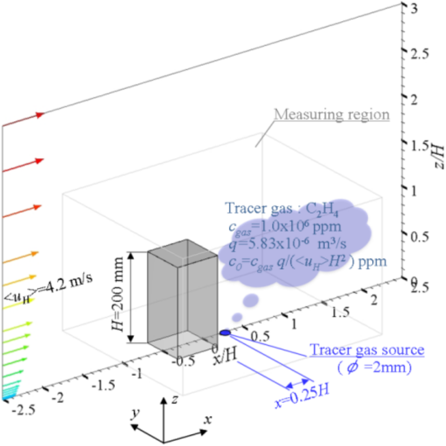
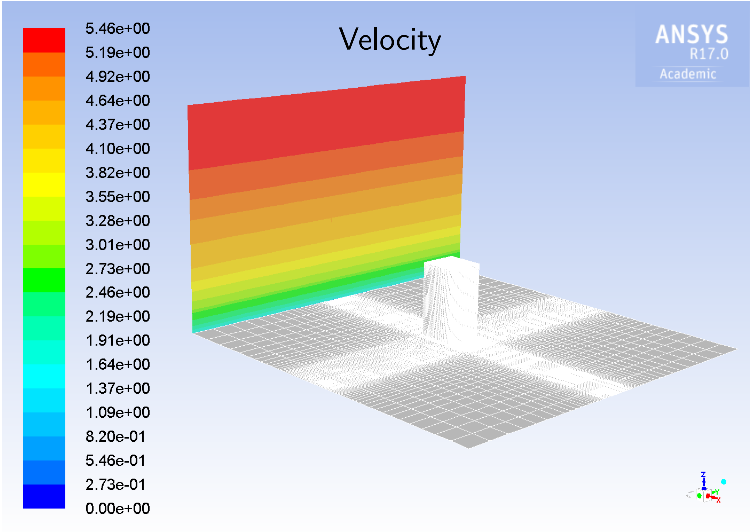


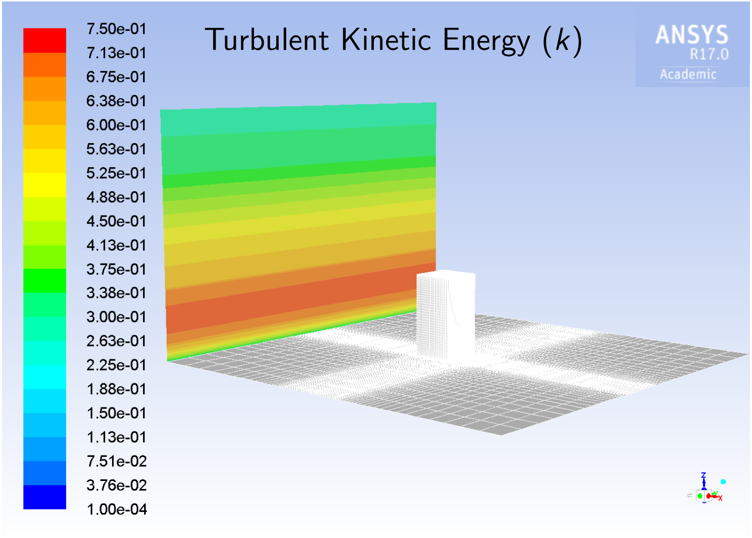
Figure 1 Flow Field Measured for This Database

[7]

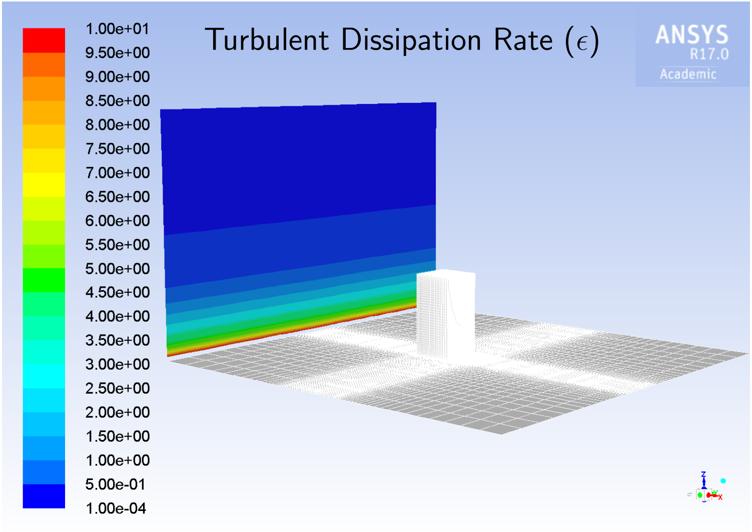
Boundary Conditions and Parameters Cont.



Boundary Conditions and Parameters Cont.

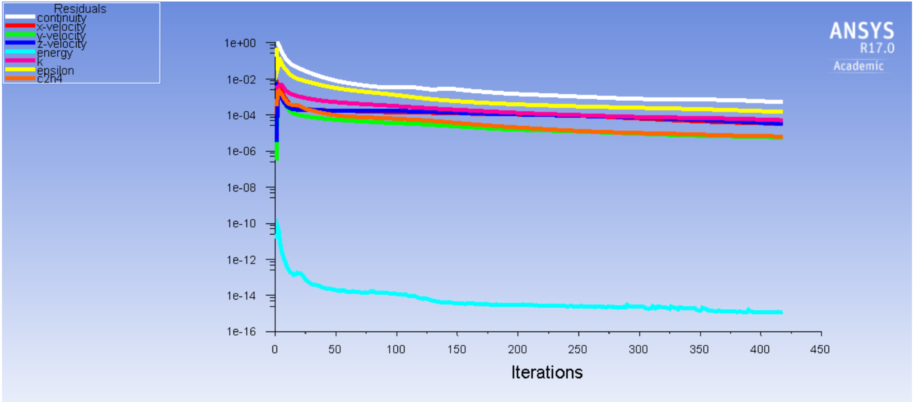


Boundary Conditions and Parameters Cont.

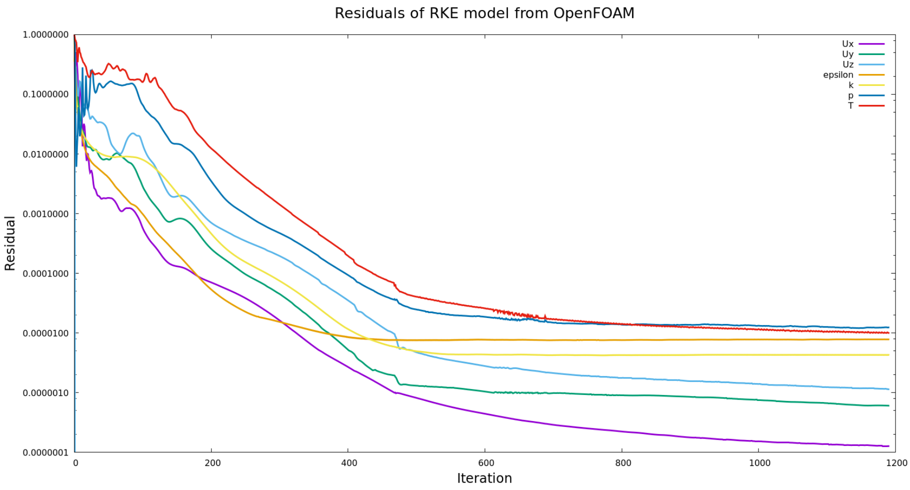


Outline

Results


Residuals
continuity
x-velocity
y-velocity
z-velocity
energy
k
epsilon
c2h4
1e+00
1e-02
1e-04
1e-06
1e-08
1e-10
1e-12
1e-14
1e-16
0
50
100
150
200
250
300
350
400
450
Iterations
ANSYS
R17.0
Academic

Results Cont.



Results Cont.

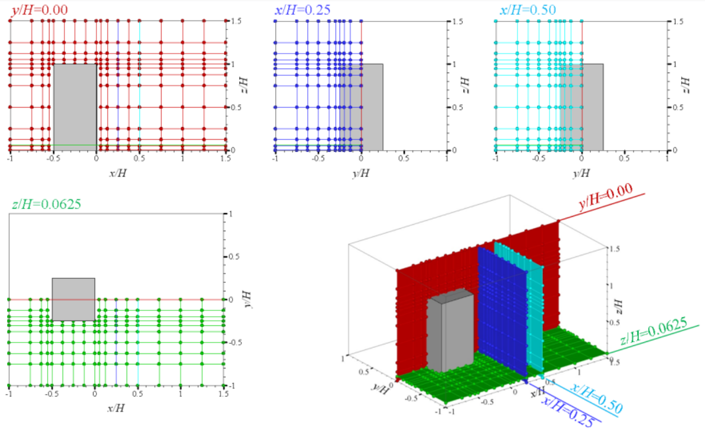
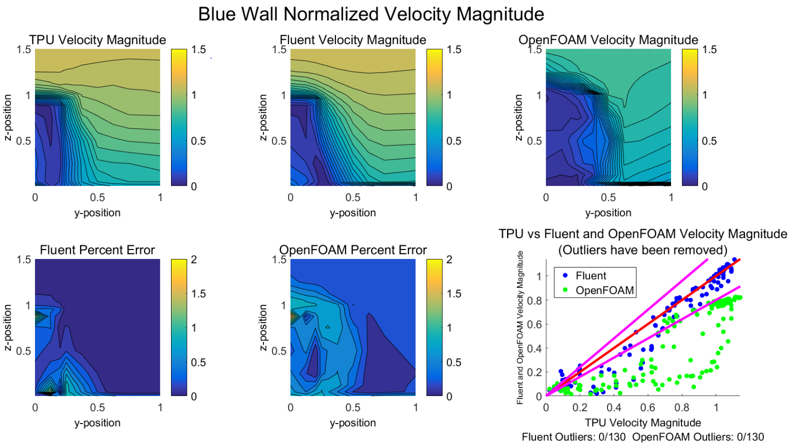


Figure 3 Measurement Point Locations

[7]

Results Cont.



Outline

Analysis: Velocity Magnitude

	Blue		Cyan		Green		Red	
	Fluent	FOAM	Fluent	FOAM	Fluent	FOAM	Fluent	FOAM
Percent Mean Absolute Error	**0.18**	0.62	**0.26**	0.52	**0.43**	0.64	**0.44**	1.17
Percent Median Absolute Error	**0.05**	0.16	**0.09**	0.18	0.38	0.38	**0.20**	0.36
Fraction of Error Less Than 50%	**0.89**	0.82	**0.86**	0.77	0.57	**0.65**	**0.76**	0.62

Analysis: Concentration

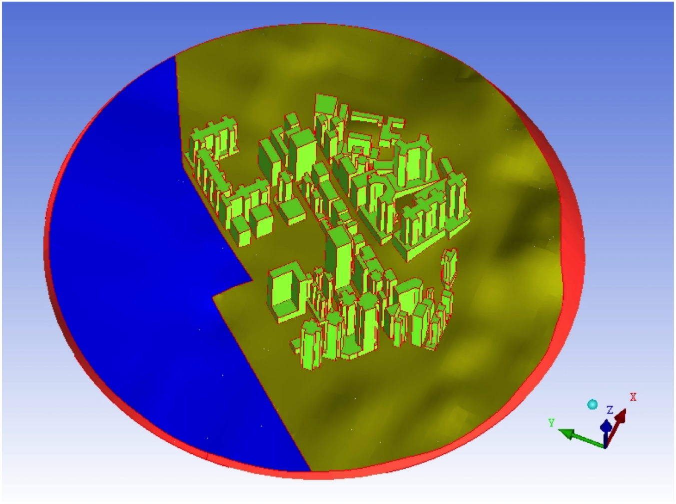
	Blue		Cyan		Green		Red	
	Fluent	FOAM	Fluent	FOAM	Fluent	FOAM	Fluent	FOAM
Percent Mean Absolute Error	**0.82**	6.91	**0.62**	1.00	**0.75**	2.16	**0.53**	9.67
Percent Median Absolute Error	**0.85**	1.01	**0.65**	1.00	**0.56**	1.01	**0.53**	1.12
Fraction of Error Less Than 50%	**0.24**	0.06	**0.36**	0.00	**0.45**	0.12	**0.47**	0.10

Outline

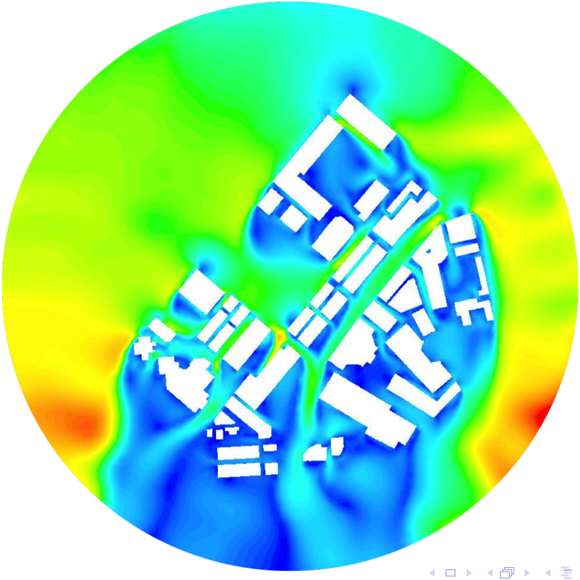
Conclusions

- Testing with Fluent justifies our choice for using the realizable $k - \epsilon$ turbulence model for this one-block case
- Comparisons between Fluent and OpenFoam show that OpenFoam does not perform as well as Fluent for the one-block case
- Future work includes refining the mesh, tuning parameters, using different solvers, and simulating other geometric models

Future Work



Future Work



Acknowledgements

AECOM

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[5] D Lafforgue. Sails: from experimental to numerical. "http://www.finot.com/ecrits/Damien%20Lafforgue/article_voiles_english_fichiers/averaging.bmp", 2007.

[6] T.H. et al. Shih. A new $k - \epsilon$ eddy viscosity model for high reynolds number turbulent flows. *Computers and Fluids*, 24(3):227–238, 1995.

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Thank you for listening.

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Any Questions?