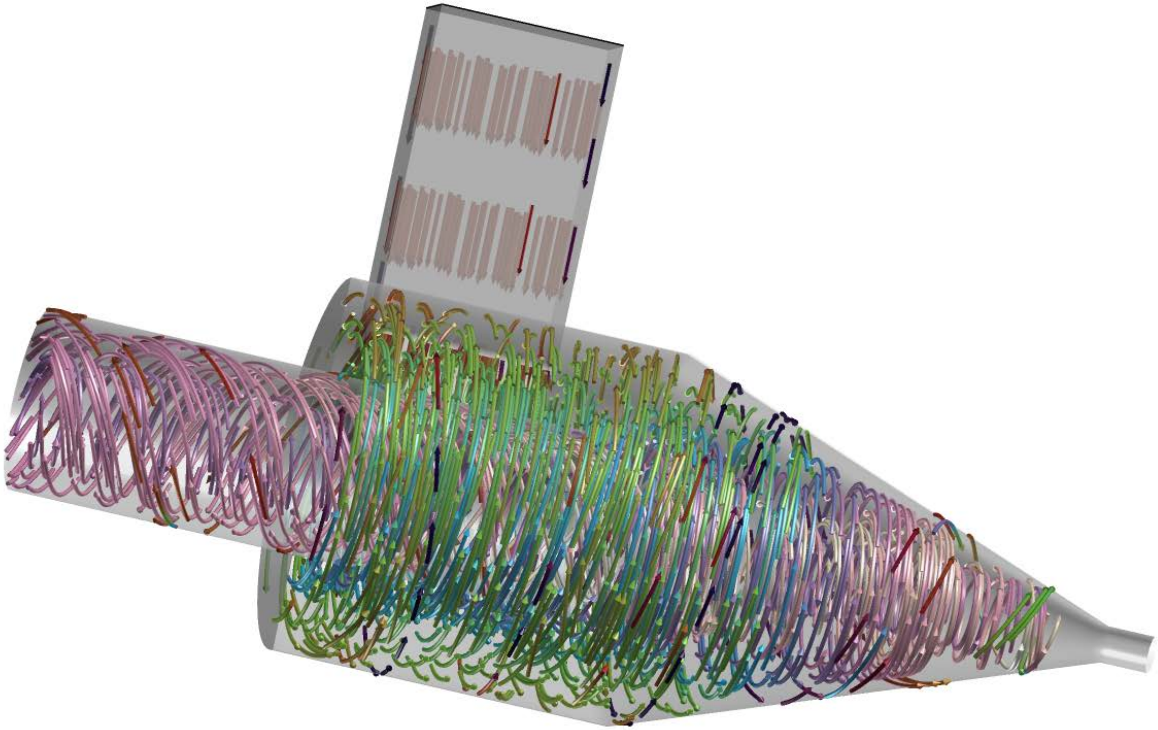


Simulation and validation of turbulent gas flow in a cyclone using Caelus

Dr Darrin W Stephens
Dr Chris Sideroff
Prof. Aleksandar Jemcov

Applied CCM

Introduction

- Cyclones play a dominant role in industrial separation of dilute particles from gas flow.
- High swirl and very large curvature of streamlines presents a modelling challenge.
- Paper’s main objective:
  - investigate the effect turbulence model selection has on the predicted mean flow behaviour within a gas cyclone.
- Numerical simulation results were compared against experimental data of Witt et al. (1999).

Turbulence models

- Three classes of turbulence models investigated
  - Two equation – offer a good compromise between numerical effort and computational accuracy.
  - Reynolds stress - applicable for the flows where the eddy-viscosity assumption is no longer.
  - LES - expected to be more accurate, particularly in complex flows where the assumptions inherent to RANS models rarely exist.

Turbulence models *cont'd*

- Two equation models (k-ω SST):

$$\partial_t k + u_j \partial_j k = \partial_j \left(\left(\nu + \sigma_k \nu_t \right) \partial_j k \right) + \min\left(f_r P_k , 10 \beta^* k \omega \right) - \beta^* k \omega$$

$$\partial_t \omega + u_j \partial_j \omega = \partial_j \left(\left(\nu + \sigma_\omega \nu_t \right) \partial_j \omega \right) + \alpha_\omega \frac{\omega}{k} \min\left(f_r P_k , 10 \beta^* k \omega \right)$$

$$- F_4 \beta_\omega \omega^2 + 2 \left(1 - F_1 \right) \frac{\sigma_{\omega_{\phi 2}}}{\omega} \partial_j k \partial_j \omega .$$

  - Standard: $f_r = 1;\ F_4 = 1$
  - Spalart and Shur Curvature Correction:

$$f_r = C_{scale} \max\left\{ \min\left(f_{rotation} , 1.25 \right) , 0.0 \right\}$$

$$f_{rotation} = \left(1 + c_{r1} \right) \frac{2 r^*}{1 + r^*} \left[1 - c_{r3} \tan^{-1}\left(c_{r2} \tilde{r} \right) \right] - c_{r1}$$

  - Hellsten curvature correction

$$F_4 = \frac{1}{1 + C_{RC} R_i} \qquad R_i = \frac{\boldsymbol{\Omega}_{mag}}{\mathbf{S}_{mag}} \left(\frac{\boldsymbol{\Omega}_{mag}}{\mathbf{S}_{mag}} - 1 \right)$$

Turbulence models *cont'd*

- Reynolds stress model:

$$\partial_t \overline{R_{ij}} + \overline{u_k}\partial_k R_{ij} = -\overline{R_{ik}}\partial_k \overline{u_j} - \overline{R_{jk}}\partial_k \overline{u_i} + \Pi_{ij} + \partial_k\left(\left(\nu + \frac{D\nu_t}{\beta^*}\right)\partial_k \overline{R_{ij}}\right)$$

$$-\frac{2}{3}\beta^* k\omega\delta_{ij}$$

  - Launder Reece Rodi (LRR) pressure strain correlation:

$$\Pi_{ij} = -C_1\varepsilon\overline{a_{ij}} + C_3 k\overline{S_{ij}}^* + C_5 k\left(\overline{a_{ik}}\,\overline{\Omega_{jk}} + \overline{a_{jk}}\,\overline{\Omega_{ik}}\right)$$

$$+C_4 k\left(\overline{a_{ik}}\,\overline{S_{jk}} + \overline{a_{jk}}\,\overline{S_{ik}} - \frac{2}{3}\overline{a_{kl}}\,\overline{S_{kl}}\delta_{ij}\right)$$

$$\overline{a_{ij}} = \frac{\overline{R_{ij}}}{k} - \frac{2}{3}\delta_{ij}$$

  - Omega equation:

$$\partial_t\omega + \overline{u_j}\partial_j\omega = \partial_j\left(\left(\nu + \sigma_\omega\nu_t\right)\partial_j\omega\right) + \alpha_\omega\frac{\omega}{2k}\overline{R_{kk}} - \beta_\omega\omega^2$$

Turbulence Models *cont'd*

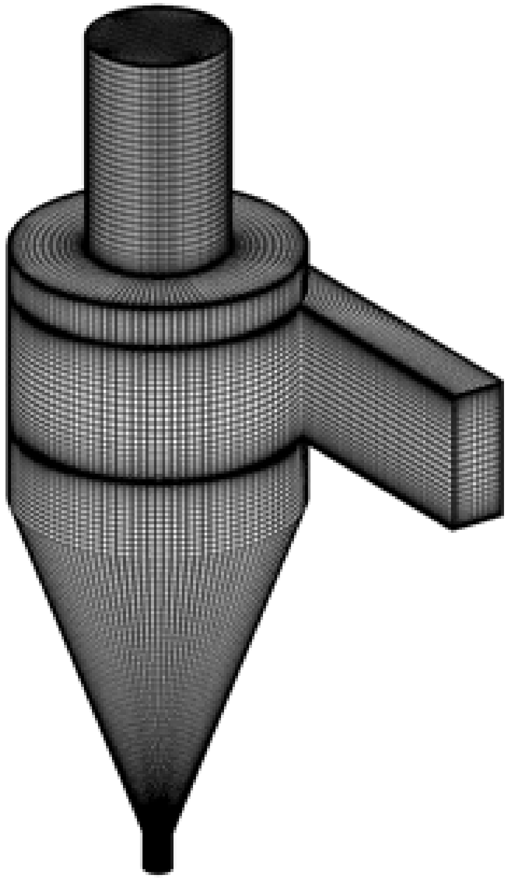
- LES sub-grid scale (SGS) models
  - Unknown stress determined from $\tau_{ij} = -2\nu_{SGS} S_{ij}$
  - Smagorinsky (1963) – an algebraic model for the SGS viscosity $\nu_{SGS} = C_s^2 \Delta^2 \mathbf{S}_{mag}$
    - Model parameter C_s is a constant
  - Coherent structure (Kobayashi, 2005) – extends Smagorinsky model using a variable C_s.

$$C_s^2 = C_{CSM} \left| F_{CS} \right|^{3/2} \left(1 - F_{CS} \right)$$

$$F_{CS} = \frac{-\partial_i \overline{u}_j \partial_j \overline{u}_i}{\left(\partial_i \overline{u}_j \right)^2} ; \; C_{CSM} = 1/22$$

Case Study

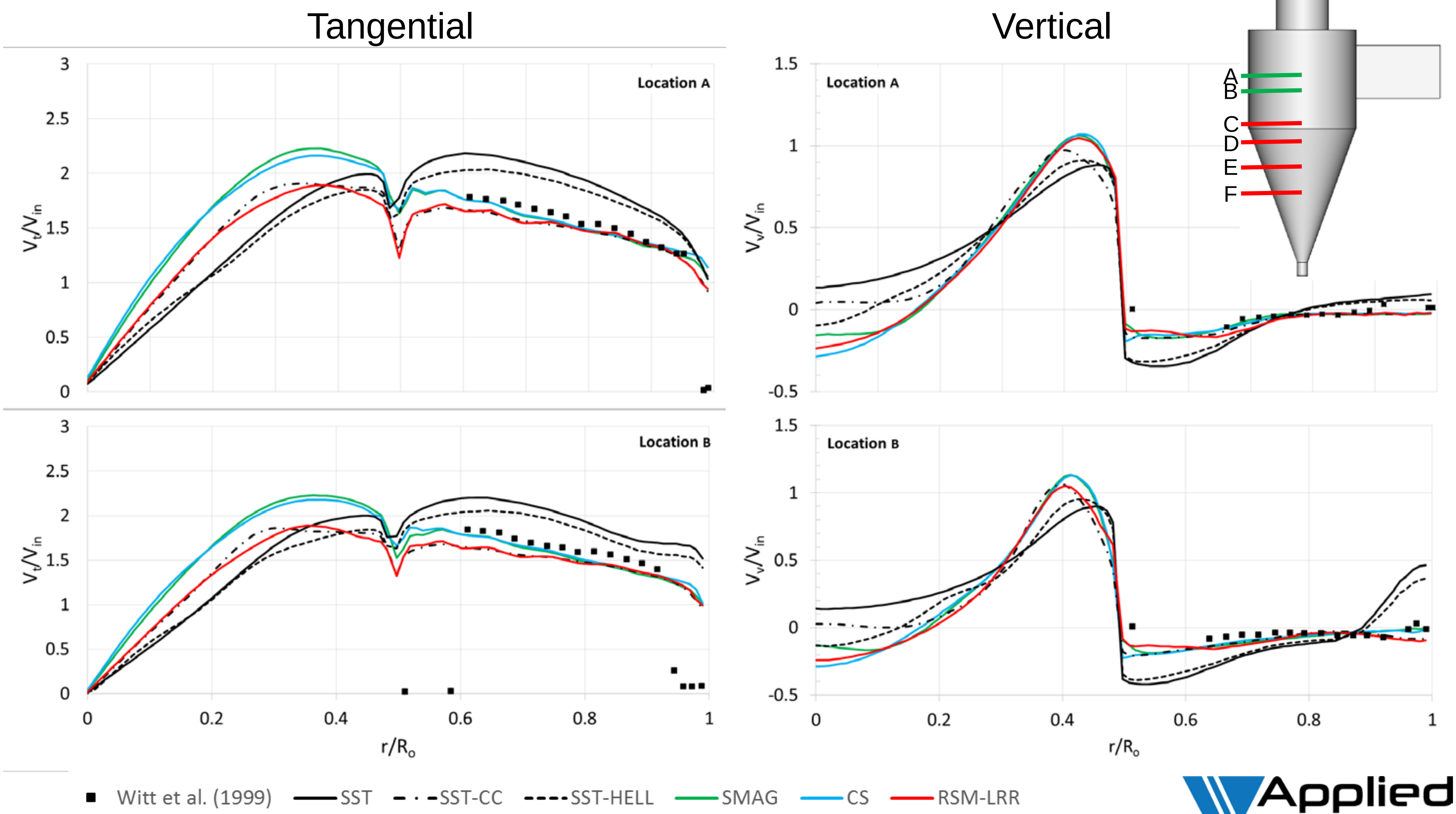
- Gas cyclone geometry
  - Outer diameter 0.39 m
  - Half-angle of 20°
  - Bottom outflow is closed for all simulations.
  - Tangential rectangular inlet.
- Grid - 606,264 hexahedral cells
- Uniform inlet velocity of 21.5 m/s.
- Neumann condition applied to all flow quantities at the vortex finder outlet.



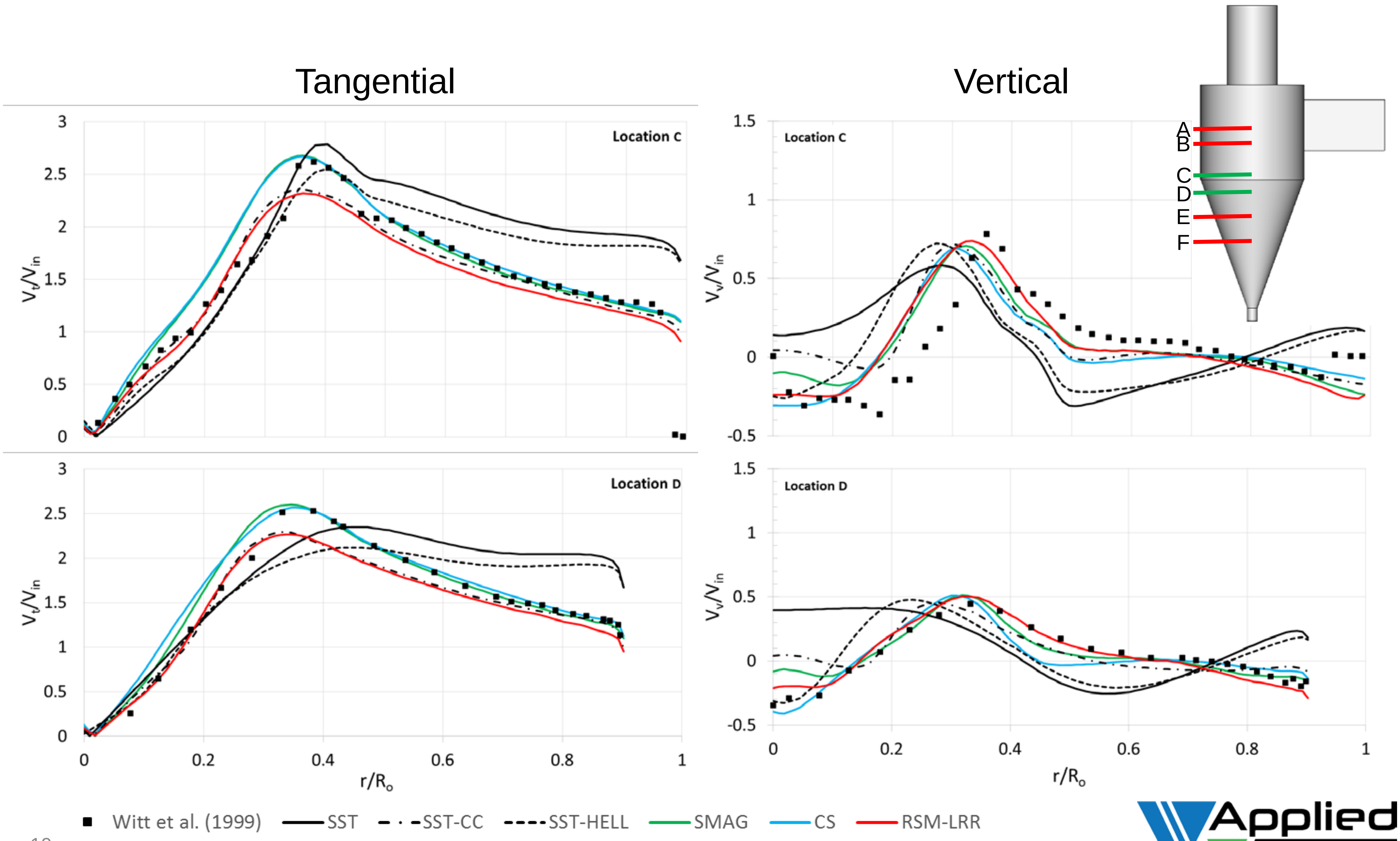
Numerical Method

- Transient Solver
  - SLIM algorithm
  - Caelus v5.04 library.
- Discretization
  - Time - 2nd order backward scheme
  - Gradients - Green-Gauss method.
  - Advection - 2nd order linear upwind multidimensional linear scheme with Barth-Jespersen limiter.
- Courant number - 5 all but RSM (0.5).
- Time averaged for 1000 residence times.

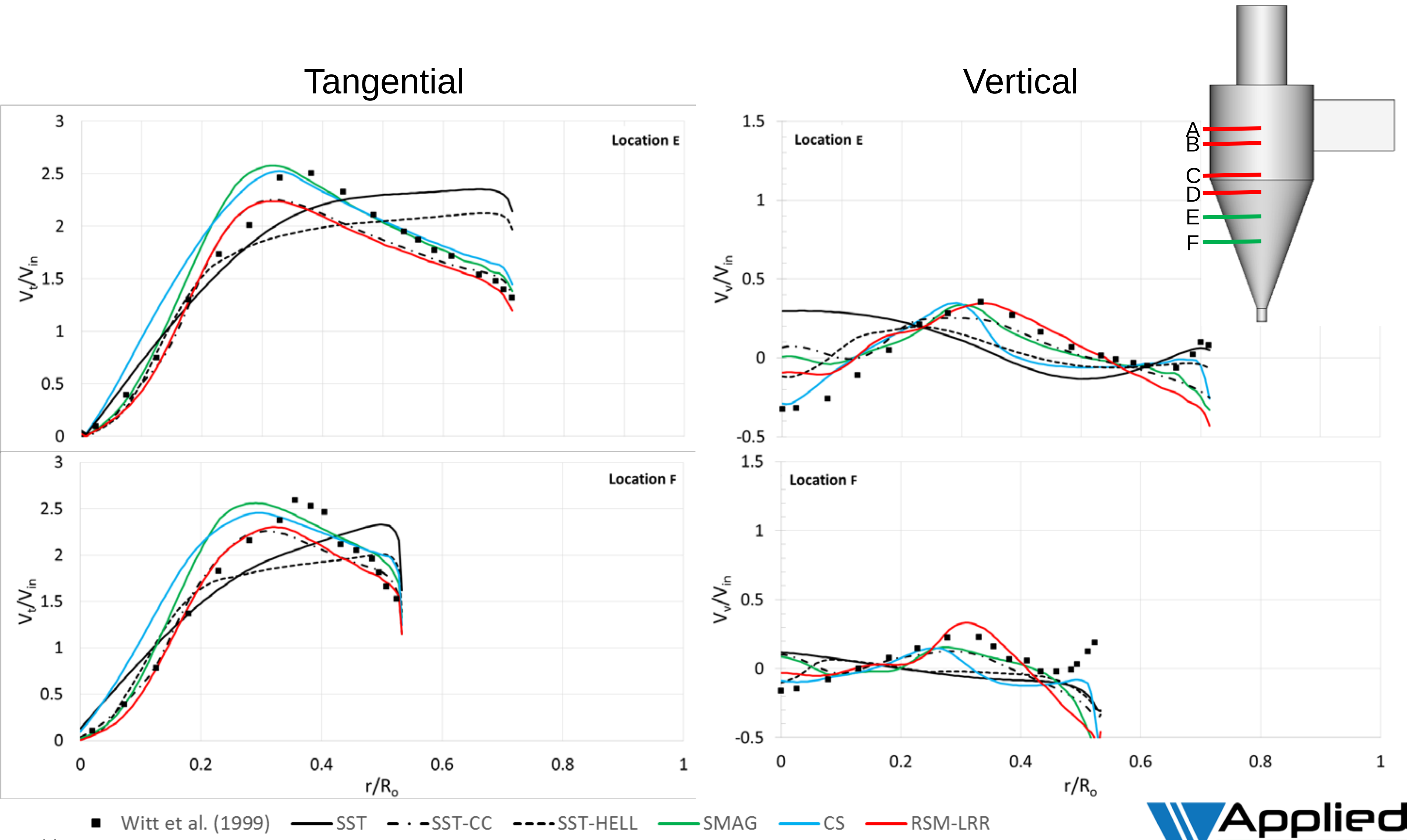
Results


Tangential
Vertical
Location A
Location B
Location A
Location B
3
2.5
2
1.5
1
0.5
0
1.5
1
0.5
0
-0.5
V_t/V_{in}
V_v/V_{in}
0
0.2
0.4
0.6
0.8
1
r/R_o
A
B
C
D
E
F
■ Witt et al. (1999)
SST
SST-CC
SST-HELL
SMAG
CS
RSM-LRR

Results *cont'd*



Results *cont'd*



Results *cont'd*

- Non-dimensionalised pressure loss coefficient

$$\xi = \frac{p'_{in} - p'_{out}}{\frac{1}{2}u_{in}^2}$$

	EXP	SST	SST-CC	SST-HELL	SMAG	CS	RSM-LRR
ξ	6.80	10.2	6.02	8.77	6.19	6.56	6.09

- Computational cost
  - 60 Intel Xeon E5-2620v3 cores per simulation

Model	CPU time (hour) per 1s flow time
SST	1.01
SST-CC	1.14
SST-HELL	1.05
SMAG	1.18
CS	1.48
RSM-LRR	10.90

Conclusion

- Turbulent flow inside cyclone simulated with different turbulence models.
- Turbulence models tested:
  - k-ω SST, k-ω SST-CC, k-ω SST-HELL,
  - Smagorinsky and Coherent structure LES,
  - LRR Reynolds Stress.
- Simulations were performed with a transient solver using version 5.04 of the Caelus library.

Conclusion

- Comparison with experimental results of Witt et al. (1999).
- Not suitable for cyclone modelling:
  - Standard k-ω SST model
  - Hellsten curvature correction
- Most accurate - Coherent structure LES.
- Least accurate - Standard k-ω SST model.
- Most expensive - LRR Reynolds Stress model.

Questions

Applied CCM
Dr Darrin Stephens
Principal Research Engineer

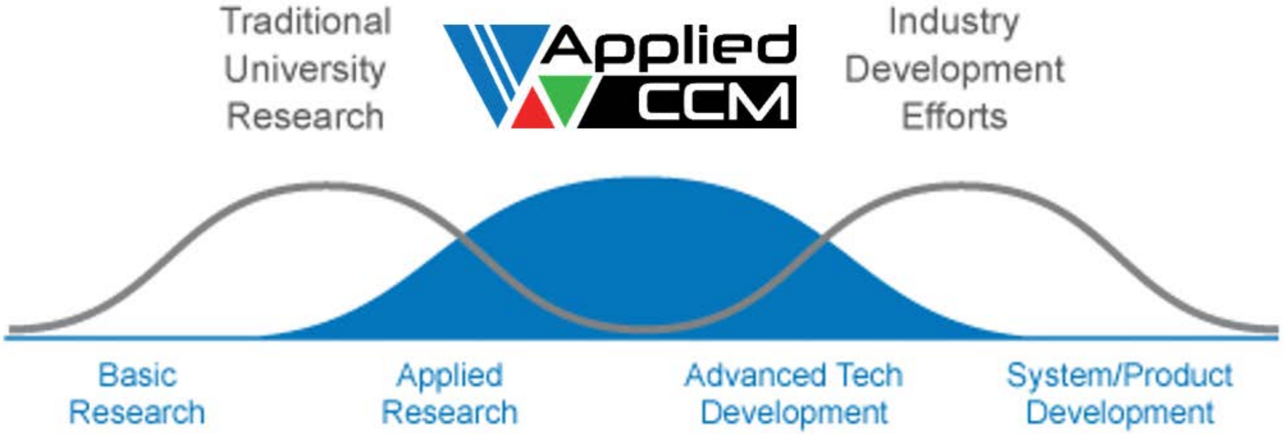
Phone: 03 8376 6962
Email: d.stephens@appliedccm.com.au
Web: www.appliedccm.com.au

What is Caelus?

- Caelus was forked from OpenFOAM
- Free and open: www.caelus-cml.com
- Support multiple platforms (Windows, Linux, Mac)
- Easy installation/compilation
- Documentation and validation cases
- Improved algorithmic robustness on non-”perfect” meshes
  - Multidimensional interpolation
  - Deferred corrections
- Improved accuracy on non-”perfect” meshes
- New compressible solvers
- New turbulence models – VLES, Coherent structure, etc
- Python wrapping, tools and utilities

About Applied CCM

- Specialise in the application, support and development of OpenFOAM.
- People
  - Darrin Stephens, Aleks Jemcov and Chris Sideroff
- Locations
  - Australia, USA and Canada
- Engage with customers as their Technology partner



Traditional University Research

Industry Development Efforts

Basic Research

Applied Research

Advanced Tech Development

System/Product Development