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

Dr Darrin W Stephens
Dr Chris Sideroff
Prof. Aleksandar Jemcov
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.

©Applied CCM. Eleventh International Conference on Computational Fluid Dynamics in the Minerals and Process Industries 2015
Turbulence models cont’d

• Two equation models (k-ω SST):

\[
\begin{align*}
\partial_t k + u_j \partial_j k &= \partial_j \left((\nu + \sigma_k \nu_t) \partial_j k\right) + \min\left(f_r P_k, 10 \beta^* k \omega\right) - \beta^* k \omega \\
\partial_t \omega + u_j \partial_j \omega &= \partial_j \left((\nu + \sigma_\omega \nu_t) \partial_j \omega\right) + \alpha_\omega \frac{\omega}{k} \min\left(f_r P_k, 10 \beta^* k \omega\right) \\
&\quad - F_4 \beta_\omega \omega^2 + 2 \left(1 - F_1 \right) \frac{\sigma_{\omega \phi_2}}{\omega} \partial_j k \partial_j \omega.
\end{align*}
\]

• Standard: \( f_r = 1; F_4 = 1 \)

• Spalart and Shur Curvature Correction:

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

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

• Hellsten curvature correction

\[
F_4 = \frac{1}{1 + C_{RC} R_i} \quad R_i = \frac{\Omega_{\text{mag}}}{S_{\text{mag}}} \left(\frac{\Omega_{\text{mag}}}{S_{\text{mag}}} - 1\right)
\]
Turbulence models cont’d

• Reynolds stress model:

\[
\frac{\partial}{\partial t} \overline{R_{ij}} + \overline{u_k} \frac{\partial}{\partial x_k} \overline{R_{ij}} = -\overline{R_{ik}} \frac{\partial}{\partial x_k} \overline{u_j} - \overline{R_{jk}} \frac{\partial}{\partial x_k} \overline{u_i} + \Pi_{ij} + \frac{2}{3} \beta^* k \omega \delta_{ij}
\]

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

• Launder Reece Rodi (LRR) pressure strain correlation:

\[
\Pi_{ij} = -C_1 \varepsilon \overline{a_{ij}} + C_3 k \overline{S_{ij}} + C_5 k \left( \overline{a_{ik} \Omega_{jk}} + \overline{a_{jk} \Omega_{ik}} \right)
\]

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

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

• Omega equation:

\[
\frac{\partial}{\partial t} \omega + \overline{u_j} \frac{\partial}{\partial x_j} \omega = \frac{\partial}{\partial x_j} \left( \left( \nu + \sigma_\omega \nu_t \right) \frac{\partial}{\partial x_j} \omega \right) + \alpha_\omega \frac{\omega}{2k} \overline{R_{kk}} - \beta_\omega \omega^2
\]
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 \( \nu_{SGS} = C_s^2 \Delta^2 S_{mag} \)
    • Model parameter \( C_s \) is a constant
  • Coherent structure (Kobayashi, 2005) – extends Smagorinsky model using a variable \( C_s \).

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

\[
F_{CS} = \frac{-\partial_i \bar{u}_j \bar{\partial}_j \bar{u}_i}{\left( \partial_i \bar{u}_j \right)^2} ; \quad C_{CSM} = \frac{1}{22}
\]
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

Witt et al. (1999)  SST  - SST-CC  - SST-HELL  SMAG  CS  RSM-LRR
Results cont’d

Tangential

Vertical

\[ \frac{V}{V_{in}} \]

Location E

Location E

Location F

Location F

\[ \frac{V}{V_{in}} \]

\[ r/R_0 \]

0 0.2 0.4 0.6 0.8 1

0 0.5 1 1.5 2 2.5 3

0 0.5 1 1.5

0 0.2 0.4 0.6 0.8 1

0 0.5 1 1.5

### Results cont’d

- **Non-dimensionalised pressure loss coefficient**

\[ \xi = \frac{p'_\text{in} - p'_\text{out}}{\frac{1}{2} u^2_{\text{in}}} \]

<table>
<thead>
<tr>
<th>Model</th>
<th>EXP</th>
<th>SST</th>
<th>SST-CC</th>
<th>SST-HELL</th>
<th>SMAG</th>
<th>CS</th>
<th>RSM-LRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST</td>
<td>6.80</td>
<td>10.2</td>
<td>6.02</td>
<td>8.77</td>
<td>6.19</td>
<td>6.56</td>
<td>6.09</td>
</tr>
<tr>
<td>SST-CC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SST-HELL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMAG</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RSM-LRR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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