Detached eddy simulation of highly swirling flows in a cylindrical hydrocyclone

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Can we make paper with a sandwich structure?

- Wood chips
- Suspension
Fractionation with a hydrocyclone

Tools needed

• Established and verified methods for

  • Experimental investigation and evaluation of fractionation efficiency. That needs measurement in fibre suspensions.

      Experimental work…

  • Efficient and accurate verified engineering methodology for virtual prototyping.

      CFD simulations
Some Important Flow Factors

- **Anisotropic Turbulent Flow** - Tangential Velocity
- **Three-Dimensional Flow**
- **Presence of Aircore** - Large Oscillations
- **Fiber Movement Within Flow Field**
- **Separate Phase for Each Class of Fibers**
- **Boundary Condition**
Cylindrical hydrocyclone for development of measurement techniques for fibre flows

- fine fraction
- vertical movable vortex finder
- coarse fraction
- cylindrical section
- feed
Measurement of tangential velocity
Swirl number

Swirl No = \frac{\text{axial flux of angular momentum}}{\text{axial flux of axial momentum}}
**Documented numerical results**

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<th>Primary Investigator</th>
<th>2D/3D</th>
<th>$Sw$</th>
<th>$Re$</th>
<th>Turbulence Models</th>
<th>Results</th>
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<tr>
<td>Sevilla (1997)</td>
<td>2DA</td>
<td>4.0</td>
<td>$8.7 \times 10^4$</td>
<td>$k-\varepsilon$</td>
<td>$T^u A^v R$</td>
<td>75-mm</td>
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<td>ARSM</td>
<td>$T^u$</td>
<td>G</td>
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<td>$T^u A^v$</td>
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<td>Montavon (2000)</td>
<td>3DT(C5)</td>
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<td>Current study</td>
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<td>8.0</td>
<td>$3.4 \times 10^5$</td>
<td>?</td>
<td>$T^u$</td>
<td>cylindrical 80-mm</td>
</tr>
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</table>

- RSM seems to work in 3D.
- Swirl numbers were no larger than 4.1 in 3D models.

We should be able to model using commercial packages without additional modifications!
Simulation parameters

- 1.8 GHz AMD Opteron 144 with 2.048 Gb DIMM DDR PC3200
- 2.8 million hexahedral elements with butterfly mesh implemented.
- LRR Reynolds Stress Model and DES tested.
LRR Reynolds stress model (Fluent)

The Reynolds stress transport equation:

$$\frac{\partial}{\partial t} (\rho u_i u_j) + \frac{\partial}{\partial x_k} (U_k \rho u_i u_j) = P_{ij} + \phi_{ij} + D_{ij} - \frac{2}{3} \delta_{ij} \rho \varepsilon.$$ 

Pressure-strain correlation:

$$\phi_{ij} = -C_1 \rho \frac{\varepsilon}{k} \left[ \frac{u_i' u_j'}{u_i' u_j'} - \frac{1}{3} \delta_{ij} \right] +$$

$$-C_2 \left[ \left( -\rho (u_i' u_k' \frac{\partial u_j}{\partial x_k} + u_j' u_k' \frac{\partial u_i}{\partial x_k}) - \frac{\partial}{\partial x_k} (\rho u_k' u_i' u_j') \right) +$$

$$\frac{1}{3} \delta_{ij} \left( \rho (u_i u_k' \frac{\partial u_j}{\partial x_k} + u_j u_k' \frac{\partial u_i}{\partial x_k}) + \frac{\partial}{\partial x_k} (\rho u_k u_i' u_j') \right) \right]$$

Boundary conditions for the Reynolds stress terms:

$$\frac{u_T'^2}{k} = 1.098, \quad \frac{u_\eta'^2}{k} = 0.247, \quad \frac{u_\lambda'^2}{k} = 0.655, \quad \frac{u_T' u_\eta'}{k} = 0.255$$
Baseline Reynolds stress model (CFX)

The Reynolds stress transport equation:

\[
\frac{\partial}{\partial t}(\rho\tau_{ij}) + \frac{\partial}{\partial x_k}(u_k\rho\tau_{ij}) = -\rho P_{ij} + \frac{2}{3}\beta' \rho \omega k \delta_{ij} - \rho \Pi_{ij} + D_{ij}
\]

Pressure-strain correlation:

\[
\Pi_{ij} = \beta'C_1 \omega \left( \tau_{ij} + \frac{2}{3} k \delta_{ij} \right) - \alpha \left( P_{ij}^{\Pi} - \frac{2}{3} P \delta_{ij} \right) - \hat{\beta} \left( D_{ij} - \frac{2}{3} P \delta_{ij} \right) - \gamma k \left( S_{ij} - \frac{1}{3} S_{kk} \delta_{ij} \right)
\]

Boundary conditions for the Reynolds stress terms:

\[
\tau_{ij} = \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right) - \frac{2}{3} \rho k \delta_{ij}
\]
Tangential velocity comparison
Reversal in axial velocities
Summary (3DT LRR)

A 3DT LRR RSM case with 2.8M elements.

- Reasonable $u_\theta$ (in comparison with the available experiment results)
- $O(10^3)$ minutes for 2000 iterations for convergence in LRR.

- Best practice does not give good results near the axis of the hydrocyclone.
2D hydrocyclone
tangential velocity profiles

- Level I
- Level II
- Level III
- Level IV

Graphs showing tangential velocity profiles at different levels.

Diagram of a hydrocyclone with levels indicated.
Unexpected 2D axial velocity
Summary (3DT LRR & 2D LRR)

A 3DT LRR RSM case with 2.8M elements (50x300).
- Reasonable $u_\theta$.
- $O(10^3)$ minutes for 2000 iterations for convergence in LRR.

A 2D LRR RSM case with 0.092M elements (80x950).
- Excellent $u_\theta$. Unexpected $u_z$.
- $O(10^2)$ minutes for convergence.

- The difficulties arise from the swirl flow physics in a cylindrical hydrocyclone.
Detached Eddy Simulation

The Spalart-Allmaras closure involving the transport equation of the turbulent kinetic viscosity, $\nu_t$, is used:

$$\frac{D}{Dt}(\rho \tilde{v}) = G_\nu + \frac{1}{\sigma_\tilde{v}} \left[ \frac{\partial}{\partial x_j} \{ (\mu + \rho \tilde{v}) \frac{\partial \tilde{v}}{\partial x_j} \} + C_{b2\rho} \left( \frac{\partial \tilde{v}}{\partial x_j} \right)^2 \right] - Y_\nu$$

The same equation is used as the RANS closure near the wall and the LES subgrid-scale model away from the wall. The switch between RANS and LES is made by

$$\tilde{d} = \min(d, C_{des} \Delta)$$
Tangential velocity comparison

Level I

Level II

Level III

Level IV
Reversal in axial velocities
Patterns in radial velocity (Level II)
Summary (3DT LRR, 2D LRR & 3DT DES)

A 3DT LRR RSM case with 2.8M elements (50x300)
• Reasonable $u_\theta$.
• $O(10^3)$ minutes for 2000 iterations for convergence in LRR.

A 2D LRR RSM case with 0.092M elements (80x950)
• Excellent $u_\theta$, Unexpected $u_z$.
• $O(10^2)$ minutes for ~2000 iterations for convergence in LRR.

A 3DT DES case with 2.8M elements (50x300)
• Good $u_\theta$, More physical $u_z$.
• $O(10^4)$ minutes for 1 hydrocyclone fluid residence time in DES.
Conclusion

● The 3D LRR results shown represent the best solution achievable with reasonable desktop computing power.
● The 2D LRR model can afford the mesh resolution necessary to simulate high swirling flow in a cylindrical hydrocyclone.
● The employment of DES gives a solution closer to the experiment at the same mesh resolution.
● DES is able to accurately model highly swirling flow.
Future Work

- Continue current DES for another residence time
- Model swirling flow without the effect of the vortex finder.

- Find/conduct experimental work using non-intrusive measurement devices and obtain tangential, axial and radial velocity profiles for validation.
Acknowledgements

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