Modeling the Swirling Flow of a Hydrocyclone

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Presentation overview

• Swirling flows in hydrocyclones
• Experimental values of the simulated flow
• Physical model and governing equations
• Numerical results
• Conclusions
Swirling flows in hydrocyclones

3D swirling flow confined in cylinder-conical geometries [1,2,3,4,5]

- **Tangential velocity** $v_\theta$ → *Rankine vortex*
  
  $v_\theta = k_1 r$  *forced vortex*  (rotation of a rigid body)
  
  $v_\theta = k_2 / r$  *free vortex*  (potential vortex)

- **Axial velocity** $v_z$ → *two opposite flows*
  
  a flow direct to the apex and a reverse flow direct to the vortex finder

- **Radial velocity** $v_r$ → *small* ($10^{-2} \text{ m/s}$)

- **Air core** → controls the liquid splitting to the outlets
Swirling flows in hydrocyclones

From experimental works (LDV) we know that the flow in a hydrocyclone has the following properties:

⇒ velocity profiles of $v_z$ and $v_\theta$ are not completely axisymmetric
⇒ $v_z, v_\theta$, and their RMS values $\sigma_z$ and $\sigma_\theta$, only change their magnitude with pressure $\Delta p$
⇒ $v_z$ changes with $z$
⇒ turbulence is neither homogeneous nor isotropic: $\sigma_z$ and $\sigma_\theta$ are different and depend on $z$ and $r$
⇒ the position of the air core depends on $\Delta p$ and the ratio $D_{VF}/D_D$ (vortex finder diameter/apex diameter)
Computational work: geometry and experimental values

dimensions of diameters and heights given in mm

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet flowrate $Q$</td>
<td>2.50 l/s</td>
</tr>
<tr>
<td>Inlet area $A= 43 \text{ mm} \times 16 \text{ mm}$</td>
<td>0.688x10$^{-3}$ m$^2$</td>
</tr>
<tr>
<td>Inlet velocity $V_{in}$</td>
<td>3.63 m/s</td>
</tr>
<tr>
<td>Pressure drop $\Delta p$</td>
<td>62.05 kPa</td>
</tr>
<tr>
<td>Water dynamic viscosity $\mu$</td>
<td>10$^{-3}$ Pa·s</td>
</tr>
<tr>
<td>Water density $\rho$</td>
<td>10$^3$ kg/m$^3$</td>
</tr>
<tr>
<td>Diameter $D$ of the hydrocyclone</td>
<td>102 mm</td>
</tr>
<tr>
<td>Mean axial velocity inside the hydrocyclone $V=4Q/\pi D^2$</td>
<td>0.306 m/s</td>
</tr>
<tr>
<td>Reynolds number $Re= \rho VD/\mu$</td>
<td>3.12x10$^4$</td>
</tr>
</tbody>
</table>

**tangential inlet:**
**generation of the vortex flow**
Computational work: hypothesis of the model

Dimensions of diameters and heights given in mm

- Model is 3D
- Flow is stationary, turbulent, single phase, incompressible and Newtonian
- Air core is modeled as a conical solid tube with known (by LDV) diameters (water is the only phase in the system)
- Velocity is specified on the inlet
- Turbulence is modeled by the RANS equations, using $v_2-f$ turbulence model with default parameters
- Turbulence intensity of 5% and turbulence length scale of 0.07 $D_{eq}$ are set at the inlet ($D_{eq} = \text{equivalent diameter}$)
- No slip conditions are assumed on the solid walls
- Slip conditions are considered on the tube walls of the air core
- Zero normal stress is the boundary condition at the outlets
Equations: RANS and v2-f turbulence model

\[ \rho \nabla \cdot \mathbf{U} = 0 \]

\[ \rho \mathbf{U} \cdot \nabla \mathbf{U} + \nabla \cdot (\rho \mathbf{u}' \mathbf{u}') = -\nabla \mathbf{P} + \nabla \cdot \mu (\nabla \mathbf{U} + (\nabla \mathbf{U})^T) + \mathbf{F} \]

\( \rho \mathbf{u}' \mathbf{u}' \) is the Reynolds stress tensor

- \( \rho \mathbf{u}' \mathbf{u}' \) computed by using the Boussinesq hypothesis and relating it to mean velocity gradients and turbulent viscosity

- v2-f turbulence model assumes turbulent viscosity as based on the velocity fluctuations \( \mathbf{v}'^2 \) normal to the streamlines, making it possible to represent turbulence anisotropy [15]
Solution with Comsol Multiphysics 5.3a

free tetrahedral volumes, *fine* (size 1) element in the hydrocyclone and *finer* (size 2) element on the solid walls

nine boundary layers on the solid walls, using default values of the software

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum element of size 1</td>
<td>6 mm</td>
</tr>
<tr>
<td>minimum element of size 1</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>maximum element of size 2</td>
<td>6 mm</td>
</tr>
<tr>
<td>minimum element of size 2</td>
<td>0.2 mm</td>
</tr>
</tbody>
</table>

• a **first study** (*Wall Distance Initialization*) to calculate the reciprocal wall distance of the v2-f turbulence model

• a stationary **second study** to compute the swirling turbulent flow

the number of degrees of freedom is $1.2 \times 10^5$ for the first study and $9.5 \times 10^5$ for the second study
Numerical results: streamlines in the hydrocyclone

The general flow pattern is well simulated.

Reverse flow to the vortex finder.

Flow direct to the apex.
Numerical results: flow split is computed

vortex finder outlet: BC is zero normal stress

overflow to the vortex finder
\[ Q_o = 1.9754 \text{ l/s} \]

inlet flow
\[ Q = 2.5 \text{ l/s} \]

flow split computed and not set before relative error is 1.65%
it depends also on the air core diameters

air core: modeled as a solid cone

underflow to the apex
\[ Q_u = 0.4833 \text{ l/s} \]

cone diameter = 14 mm

apex outlet: BC is zero normal stress
Numerical computations: velocity profiles

Overflow

Inlet flow

Underflow

$z = -180 \text{ mm}$

forced vortex
Numerical computations: velocity profiles

Overflow

Inlet flow

Underflow

not a free vortex, although a better profile than at \( z = -180 \) mm

forced vortex
Velocity profiles: comparison with LDV measurements

- Same locus of zero axial velocity
- Very coincident upward maximum (2.2 m/s) and downward maximum (0.9 m/s) values of axial velocity, same axial flow profile

LDV [14]

- Forced vortex is right
- Maximum swirl velocity, its position and free vortex are not predicted
Conclusions

• The swirling flow in a hydrocyclone has been simulated by developing a 3D model of the flow
• The anisotropic turbulence of the flow has been modeled by using RANS and the v-2f turbulence closure
• The general flow pattern is quite well reproduced
• Axial velocity profiles and numerical values are well solved for
• Tangential velocity profiles differ from LDV measurements, the free vortex is not predicted
• A more complete model might be developed, including the modeling of the air core and a better performance of the turbulence (new Comsol feature LES)
References

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