A Comparison of Actuator Disk Models For Axial Flow Fans in Large Air-Cooled Heat Exchangers

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Simplified Fan Models

Why?

- Numerical modelling is used to predict the performance of air-cooled heat exchangers under a variety of operating conditions.
- System complexity – Large numbers of fans.
- High computational and economic expense of explicit fan models.

A large air-cooled heat exchanger (adapted from Louw (2015)).
The Actuator Disk Model

Overview

• Simplified fan model developed by Thiart and von Backström (1993).
• Represents a fan by introducing momentum source terms on the plane in which the fan acts
• Source terms are calculated by blade element theory and aerofoil data
• Sensitive to distorted in flows
• Successfully used in several studies
• Shortcoming: Performs poorly at low flow rates
Actuator Disk Models

Overview of models

• Standard Actuator Disk Model
  – Performs well at design flow rate, however does not perform well at low flow rates

• Two modified versions of the standard ADM have been developed with the aim of improving fan performance prediction at low flow rates
  – The Extended Actuator Disk Model (EADM) of van der Spuy (2011)
Actuator Disk Models

Comparison

- Models are compared to experimental data in terms of fan static pressure, power and fan static efficiency.
- The velocity prediction of the models is compared to the results of the Periodic 3 Dimensional Model (P3DM) of Louw(2015). The P3DM is a highly detailed numerical model of a single blade passage in the test fan.
- This was done as the experimental measurement of velocity profiles directly up and downstream of the blades is not possible.
# Experimental Fan

## The B2a Fan - Dimensions

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shroud Diameter</td>
<td>1.542 m</td>
</tr>
<tr>
<td>Blade Number</td>
<td>8</td>
</tr>
<tr>
<td>Fan Diameter</td>
<td>1.536 m</td>
</tr>
<tr>
<td>Hub/tip Ratio</td>
<td>0.4</td>
</tr>
<tr>
<td>Aerofoil</td>
<td>NASA LS 413</td>
</tr>
</tbody>
</table>

B2a fan schematic (adapted from Louw (2015))
# Experimental Fan

## The B2a Fan – Performance Specification

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{max}}$</td>
<td>6000 W</td>
</tr>
<tr>
<td>$\Delta p_{Fs}$</td>
<td>210 Pa</td>
</tr>
<tr>
<td>$\dot{V}$</td>
<td>16 m$^3$/s</td>
</tr>
<tr>
<td>$N$</td>
<td>750 rpm</td>
</tr>
</tbody>
</table>

- Near free vortex design
- Designed to perform well at decreasing flow rates
Experiments

Fan Test Facility

Fan test facility schematic (Adapted from Louw (2015))
The Actuator Disk Model

Theory

• Fan blades replaced by 3 cell zones
• Actuator disk introduces fan forces into the Navier-Stokes equation source terms
• Upstream and downstream disks are used to compute the average relative velocity angles in order to compute angle of attack

Description of the ADM (Adapted from Louw (2015))
The Actuator Disk Model

Theory

- Once angle of attack is known, the aerofoil lift coefficient can be calculated.
- Momentum source terms are calculated as follows

\[
L = \frac{1}{2} \rho \omega_{\theta z, \infty}^2 C_L \chi h. \delta r
\]

\[
D = \frac{1}{2} \rho \omega_{\theta z, \infty}^2 C_D \chi h. \delta r
\]

\[
F_z = L \cos \beta_{\infty} + D \sin \beta_{\infty}
\]

\[
F_\theta = L \sin \beta_{\infty} - D \cos \beta_{\infty}
\]

\[
\Sigma \frac{F_z}{dV} = \frac{F_z}{\Delta z \delta p} \quad \Sigma \frac{F_\theta}{dV} = \frac{F_\theta}{\Delta z \delta p}
\]

\[
\Sigma \frac{F_r}{dV} = 0
\]
Attempts to improve low flow rate performance by CL augmentation

The reasoning behind this model stems from Himmelskamp (1947)

The EADM is based on the model of Gur and Ronsen (2005)

The EADM attempts to enhance performance at low flows by extending the linear section of the aerofoil lift coefficient vs angle of attack curve
The Reverse Engineered Empirical ADM

Theory

- The REEADM makes use of lift drag and radial force data extracted from the P3DM explicit fan blade model
- Aims to account for radial forces
- Model aims to be less computationally expensive than the P3DM while offering better performance than the ADM
- $R = F_r$
- $C_r = \frac{R}{0.5 \rho \omega_\infty^2 c h}$
- $\sum \frac{F_r}{dV} = \frac{F_r}{\Delta z s_p}$

Lift data used in the REEADM (Louw, 2015)
Numerical Modelling

Computational Domain
# Numerical Modelling

## Solver settings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discretisation scheme (Gradient)</td>
<td>Least square cell based</td>
</tr>
<tr>
<td>Discretisation scheme (Pressure)</td>
<td>Standard</td>
</tr>
<tr>
<td>Discretisation scheme (other)</td>
<td>QUICK/2nd order upwind</td>
</tr>
<tr>
<td>Pressure –velocity coupling</td>
<td>SIMPLE</td>
</tr>
</tbody>
</table>
## Numerical Modelling

### Mesh independence

<table>
<thead>
<tr>
<th>Cell count</th>
<th>Model</th>
<th>ADM</th>
<th>REEADM</th>
<th>EADM</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.91E+04</td>
<td>tet</td>
<td>0.102</td>
<td>0.087</td>
<td>0.105</td>
</tr>
<tr>
<td>1.19E+06</td>
<td>tet</td>
<td>0.102</td>
<td>0.086</td>
<td>0.105</td>
</tr>
<tr>
<td>3.18E+05</td>
<td>poly</td>
<td>0.102</td>
<td>0.087</td>
<td>0.105</td>
</tr>
<tr>
<td>4.90E+04</td>
<td>tet</td>
<td>0.102</td>
<td>0.085</td>
<td>0.104</td>
</tr>
<tr>
<td>7.28E+04</td>
<td>poly</td>
<td>0.102</td>
<td>0.085</td>
<td>0.104</td>
</tr>
</tbody>
</table>
Results

Fan Characterisation – Fan Power

![Graph showing power consumption vs. flow coefficient with data points for experimental data, ADM, READM, and EADM.]
Results

Fan Characterisation – Fan Static Pressure

![Graph showing Fan Static Pressure and Flow Coefficient]

- **Fan static pressure coefficient** \( \Psi_{Fs} \)
- **Flow Coefficient** \( \phi \)

**Experimental Data**
- ADM
- REEADM
- EADM
Results

Fan Characterisation – Fan Static Efficiency

![Graph showing Fan Static Efficiency vs. flow coefficient]
Results Velocity profiles

Velocity Profiles - \( \phi = 0.074 \) (7 \( m^3/s \))

Axial velocity upstream

Axial velocity downstream
Results Velocity profiles

Velocity Profiles - $\phi = 0.074$ ($7\, \text{m}^3/\text{s}$)

Radial velocity upstream

Radial velocity downstream
Results Velocity profiles

Velocity Profiles - $\phi = 0.074 \ (7 \ m^3/s)$

Tangential velocity upstream

Tangential velocity downstream
Results Velocity profiles

Velocity Profiles - $\phi = 0.168 \ (16 \ m^3/s)$

Axial velocity upstream

Axial velocity downstream
Results Velocity profiles

Velocity Profiles - $\phi = 0.168$ ($16 \, m^3/s$)

- Radial velocity upstream
- Radial velocity downstream
Results Velocity profiles

Velocity Profiles - $\phi = 0.168 \ (16 \ m^3/s)$

Tangential velocity upstream

Tangential velocity downstream
Conclusions

- All models greatly under predict the radial velocity component at low flow rates
- The EADM does improve performance in terms of characterisation at low flows
- The REEADM does not make much improvement on the other models in spite of its detail
- The extra effort of generating a full 3D CFD model in order to generate the REEADM is not justified by its performance

<table>
<thead>
<tr>
<th></th>
<th>P3DM</th>
<th>Actuator disc models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processors</td>
<td>8 CPUs (2.1-3 GHz)</td>
<td>2 CPUs (3.4 GHz)</td>
</tr>
<tr>
<td>RAM</td>
<td>15 Gb</td>
<td>32 Gb</td>
</tr>
<tr>
<td>Time</td>
<td>2-28 days</td>
<td>10-120 min</td>
</tr>
</tbody>
</table>
Conclusions

• All models give good velocity profile prediction at design flow rate
• Instability in the EADM and REEADM at high flow rates
• The standard ADM gives a good trade off between ease of implementation and fan performance and flow field prediction at higher flow rates
• The EADM gives better low flow performance and is relatively simple, there is scope for improvement
• At design conditions despite its better performance the REEADM is a less attractive modelling option than the Standard ADM due to the extra computational expense in its development
References


• Gur, O., Rosen, A., Propeller performance at low advance ratio, *Journal of Aircraft, 42*, no. 2, 2005
Thank You

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