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

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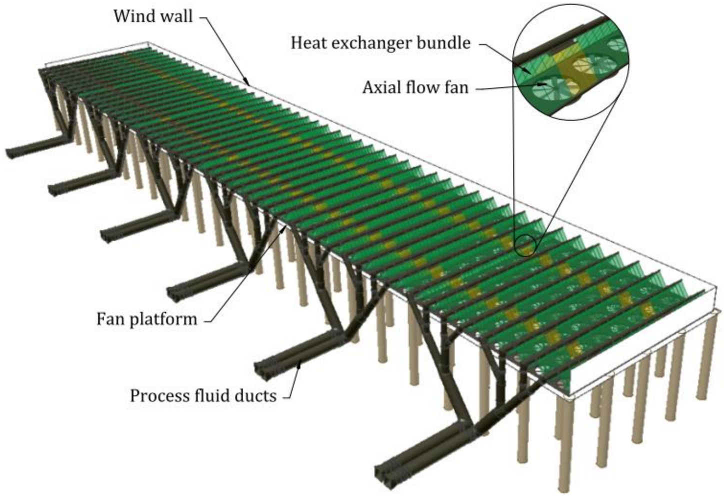
Simplified Fan Models

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)
  - The Reverse Engineered Empirical Actuator Disk Model (REEADM) of Louw (2015)

Actuator Disk Models

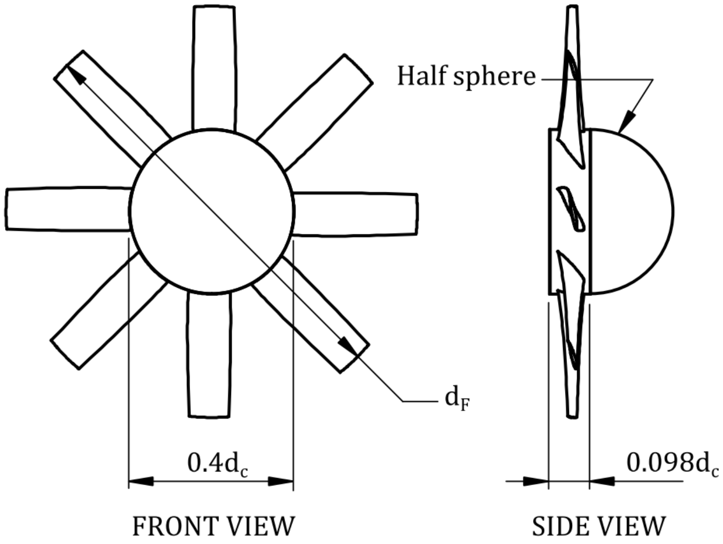
Comparison

- 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

Dimension	Value
Shroud Diameter	1.542 m
Blade Number	8
Fan Diameter	1.536 m
Hub/tip Ratio	0.4
Aerofoil	NASA LS 413



B2a fan schematic (adapted from Louw (2015))

Experimental Fan

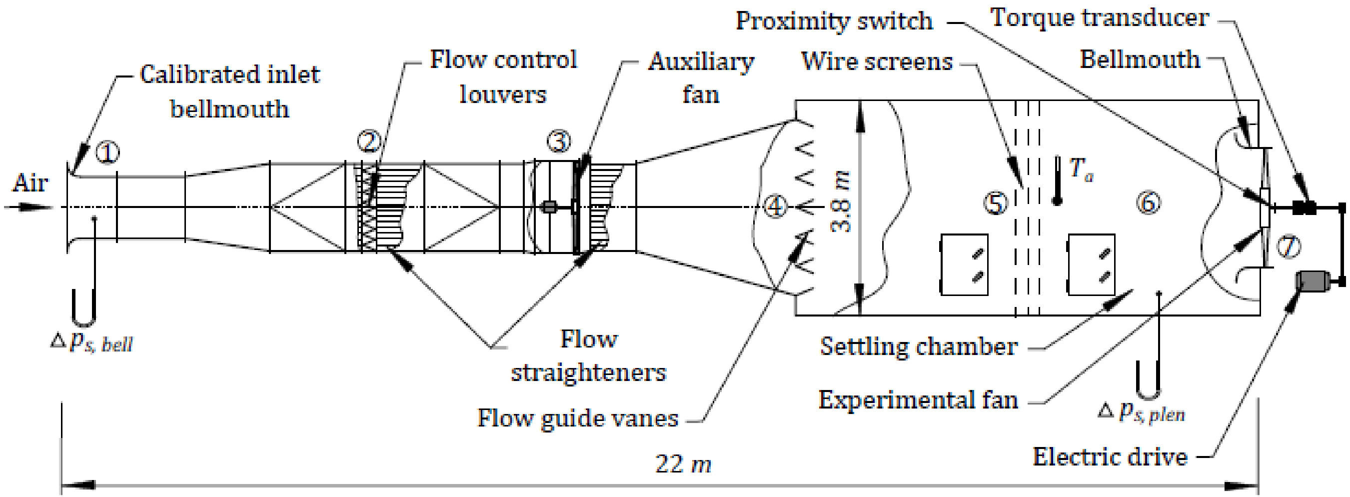
The B2a Fan – Performance Specification

Specification	Value
P_{max}	6000 W
Δp_{Fs}	210 Pa
$\dot{V}$	16 m^3/s
N	750 rpm

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

Experiments

Fan Test Facility

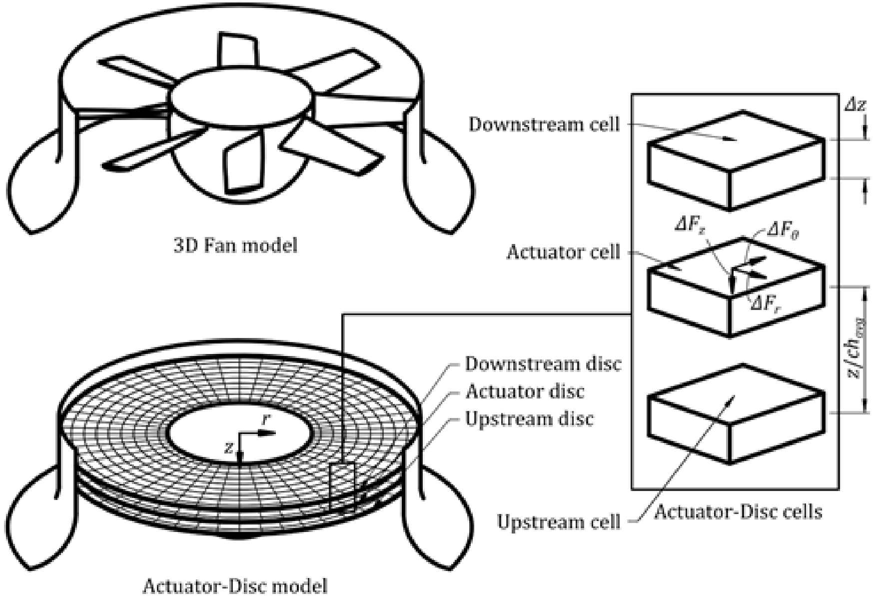


Fan test facility schematic (Adapted from Louw (2015))

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

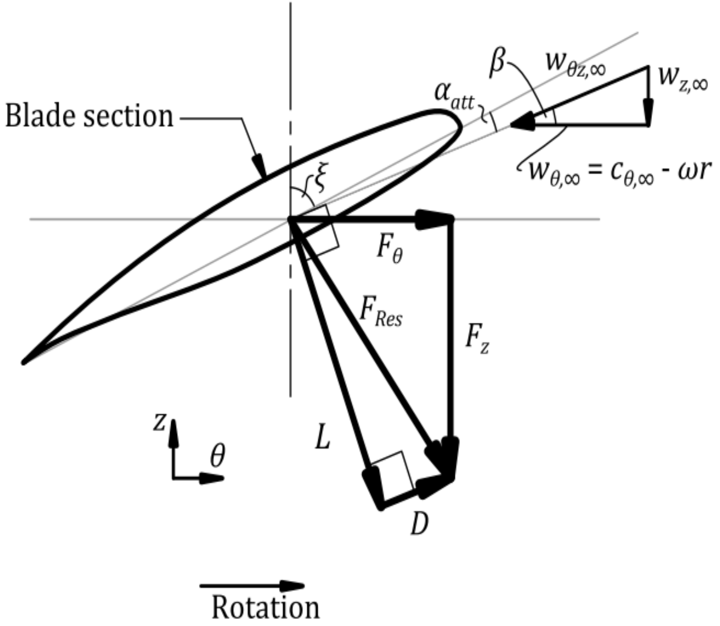


Description of the ADM (Adapted from Louw (2015))

The Actuator Disk Model

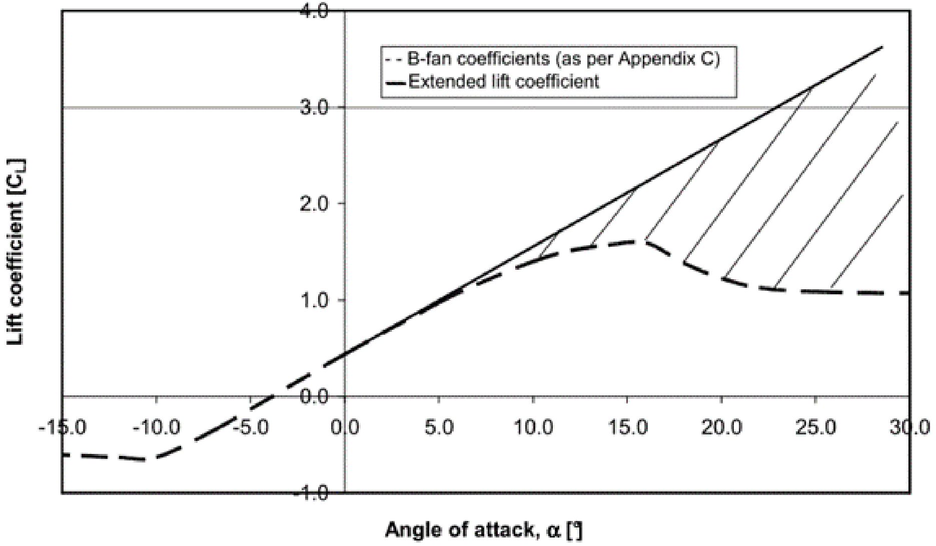
Theory

- Once angle of attack is known, the aerofoil lift coefficient can be calculated
- Momentum source terms are calculated as follows
- $L = \frac{1}{2}\rho\omega_{\theta z,\infty}^{2}C_{L}ch.\delta r$
- $D = \frac{1}{2}\rho\omega_{\theta z,\infty}^{2}C_{D}ch.\delta r$
- $F_z = L cos\beta_\infty + D sin\beta_\infty$
- $F_\theta = L sin\beta_\infty - D cos\beta_\infty$
- $\frac{\sum F_z}{dV} = \frac{F_z}{\Delta z s_p}$ $\qquad \frac{\sum F_\theta}{dV} = \frac{F_\theta}{\Delta z s_p}$
- $\frac{\sum F_r}{dV} = 0$



The Extended Actuator disk model

Theory



EADM extended lift coefficients (van der Spuy 2011)

- 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

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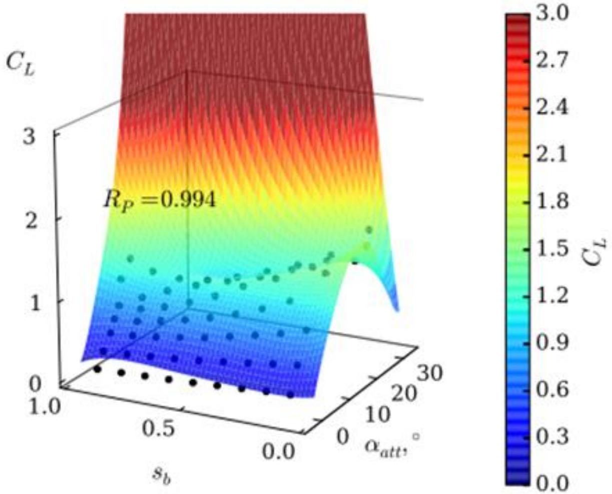
The Reverse Engineered Empirical ADM

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
- $R = F_r$
- $C_r = \dfrac{R}{0.5\rho\omega_\infty^2 ch}$
- $\dfrac{\sum F_r}{dV} = \dfrac{F_r}{\Delta z\, s_p}$



Lift data used in the REEADM (Louw, 2015)

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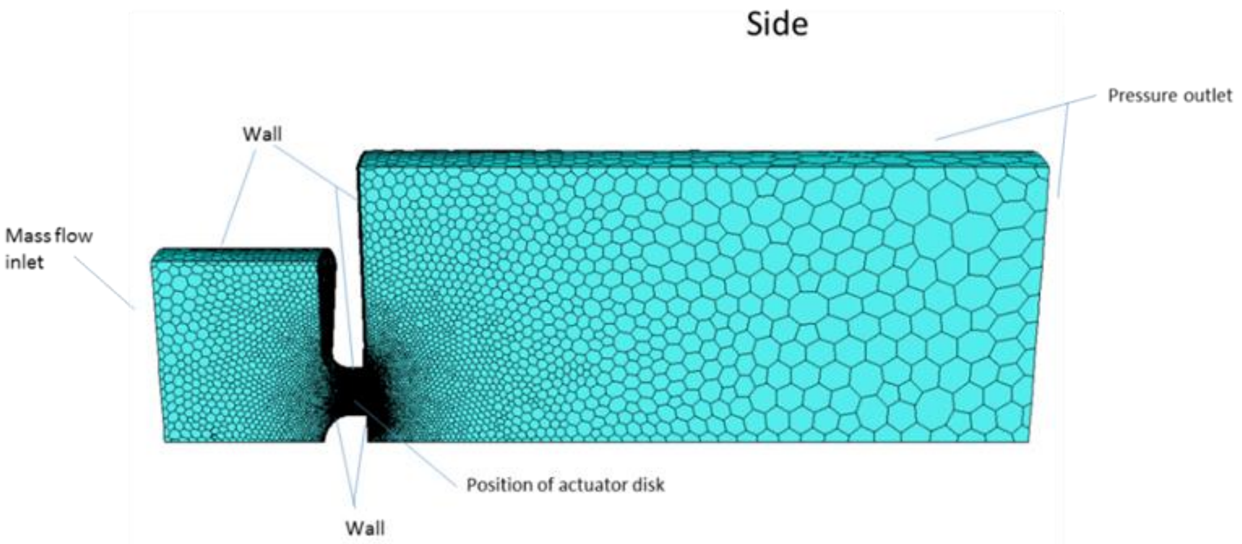
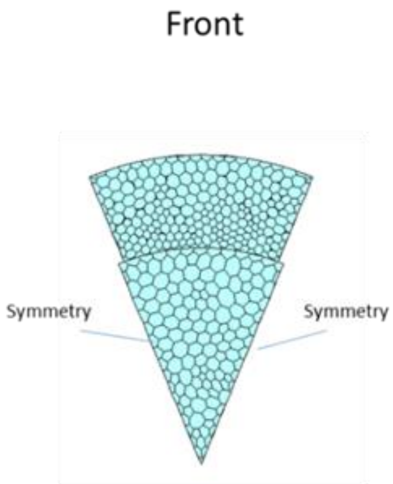
Numerical Modelling

Computational Domain





Numerical Modelling

Solver settings

Parameter	Setting
Discretisation scheme (Gradient)	Least square cell based
Discretisation scheme (Pressure)	Standard
Discretisation scheme (other)	QUICK/2nd order upwind
Pressure –velocity coupling	SIMPLE

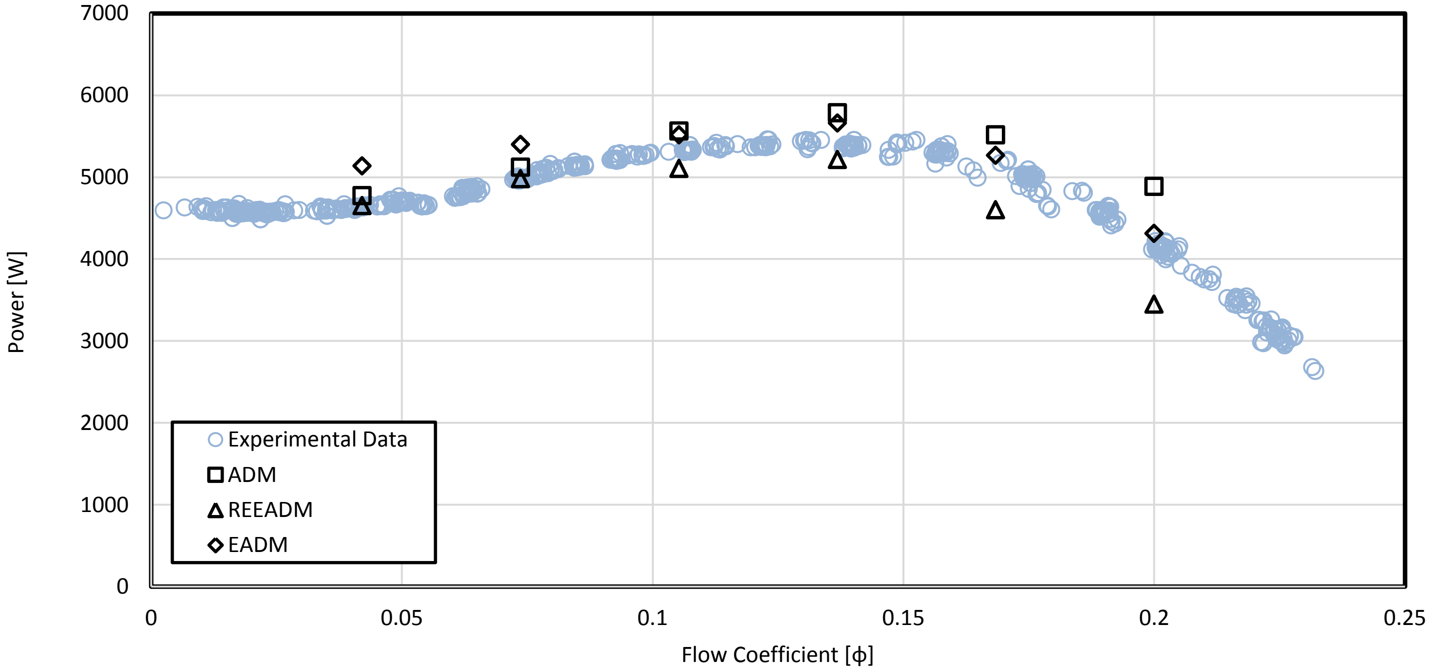
Numerical Modelling

Mesh independence

	Model	ADM	REEADM	EADM
Cell count	Mesh type	Static pressure coefficient (φ)		
7.91E+04	tet	0.102	0.087	0.105
1.19E+06	tet	0.102	0.086	0.105
3.18E+05	poly	0.102	0.087	0.105
4.90E+04	tet	0.102	0.085	0.104
7.28E+04	poly	0.102	0.085	0.104

Results

Fan Characterisation – Fan Power



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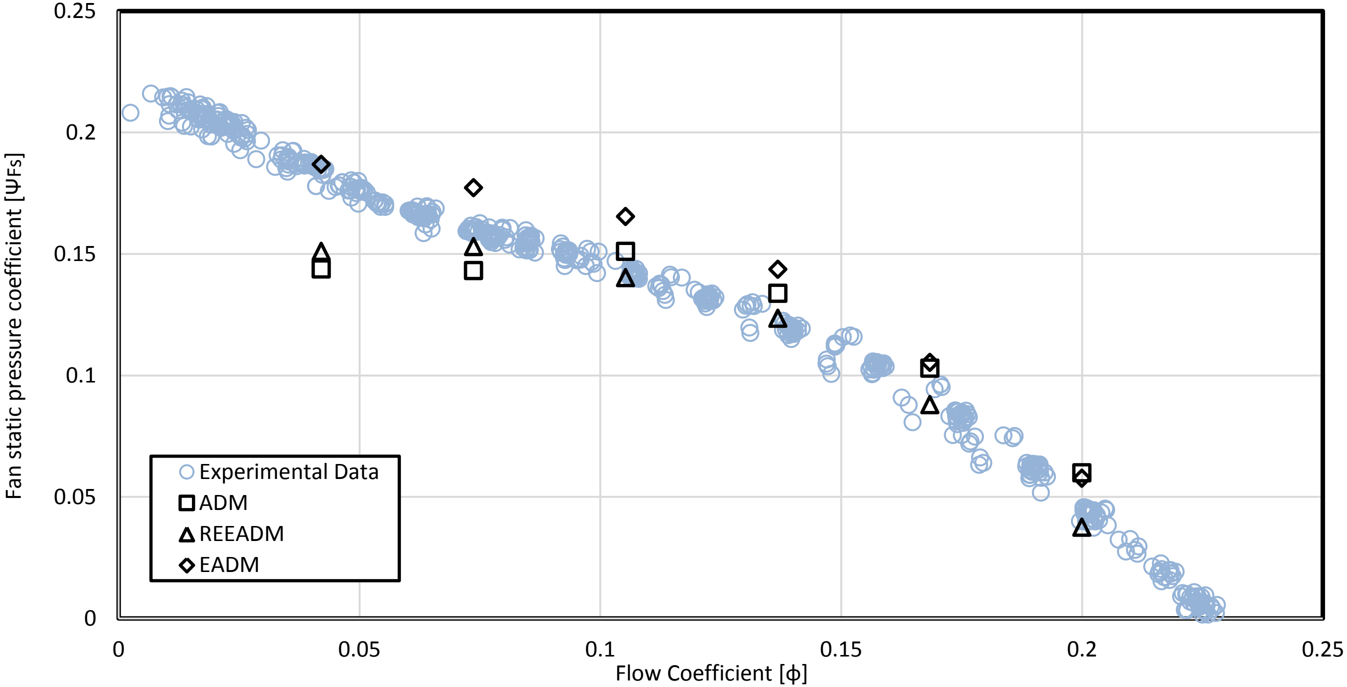
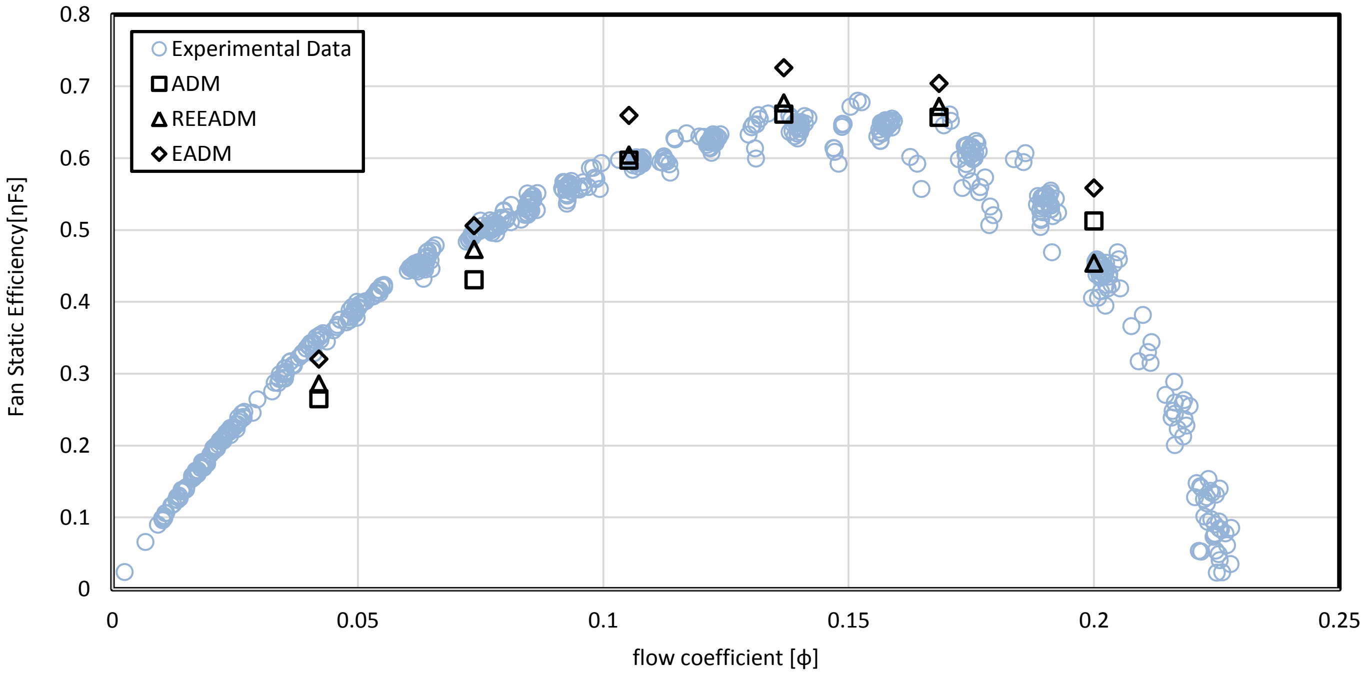
Results

Fan Characterisation – Fan Static Pressure



Results

Fan Characterisation – Fan Static Efficiency



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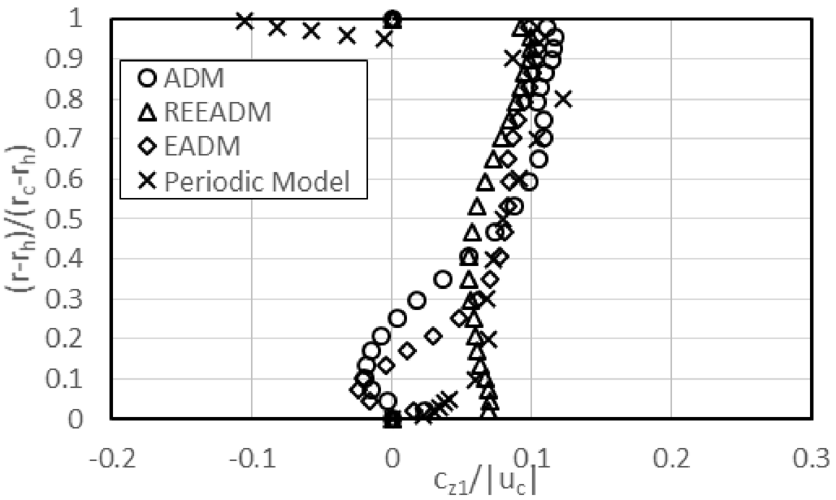
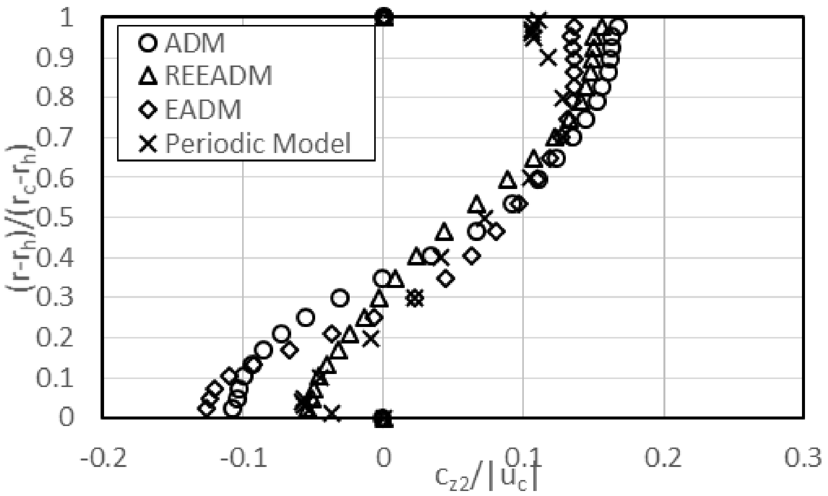
Results Velocity profiles

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



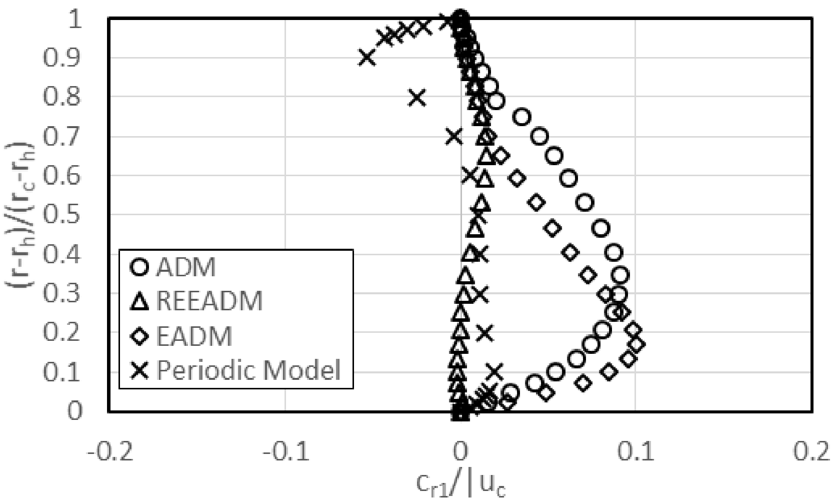
Axial velocity upstream



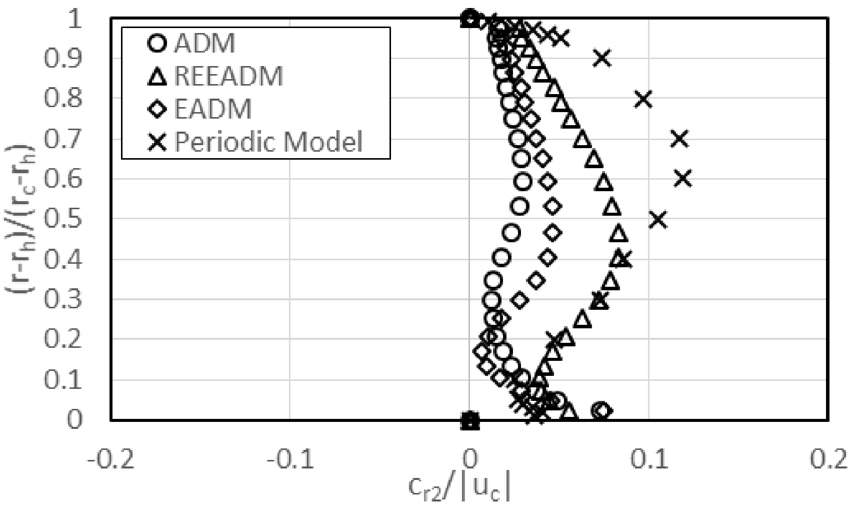
Axial velocity downstream

Results Velocity profiles

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



Radial velocity upstream



Radial velocity downstream

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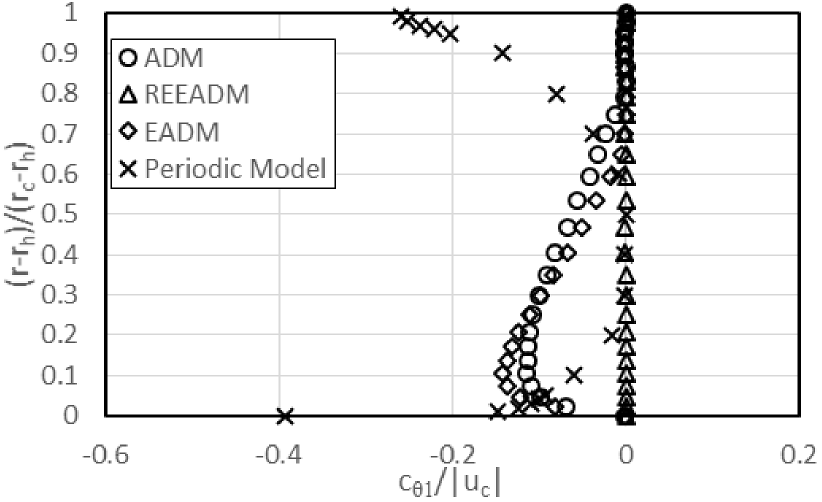
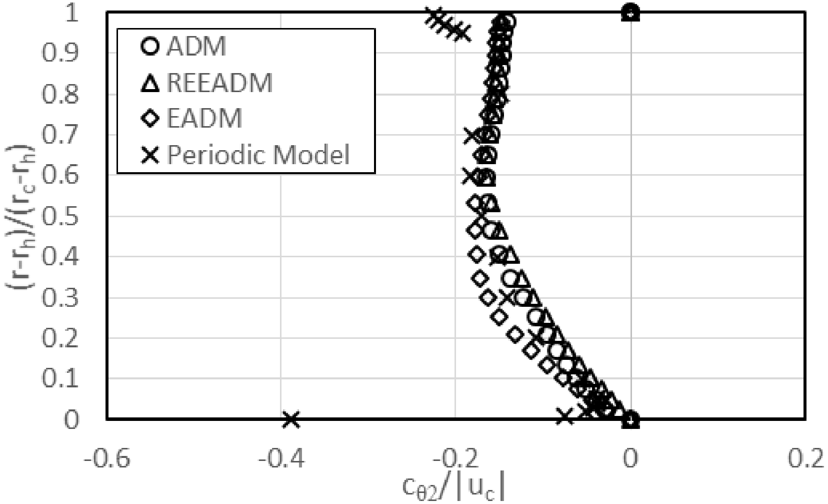


Tangential velocity upstream



Tangential velocity downstream

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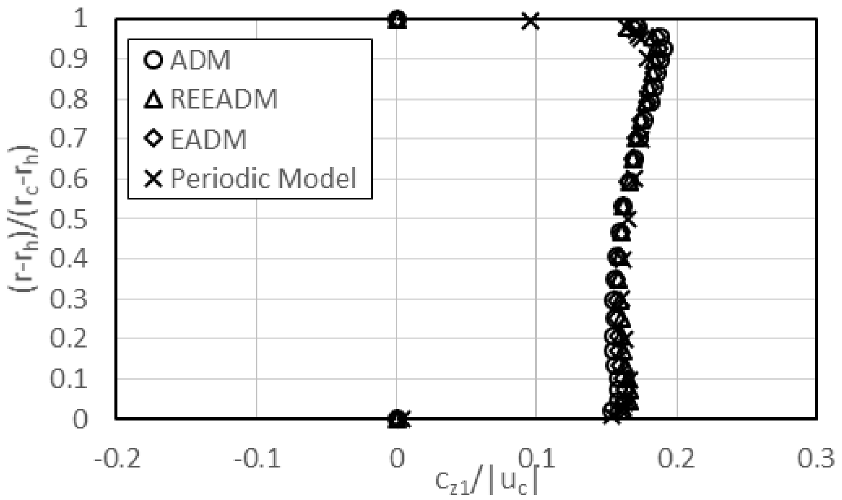
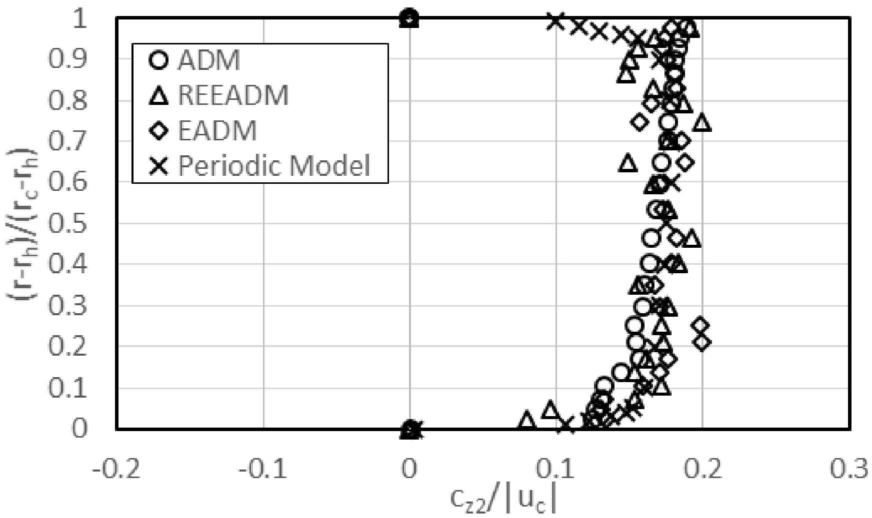
Results Velocity profiles

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



Axial velocity upstream



Axial velocity downstream

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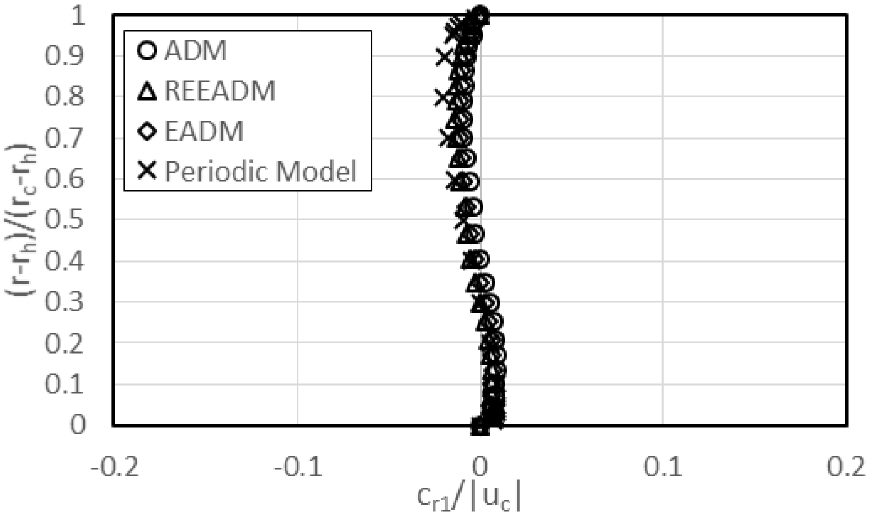
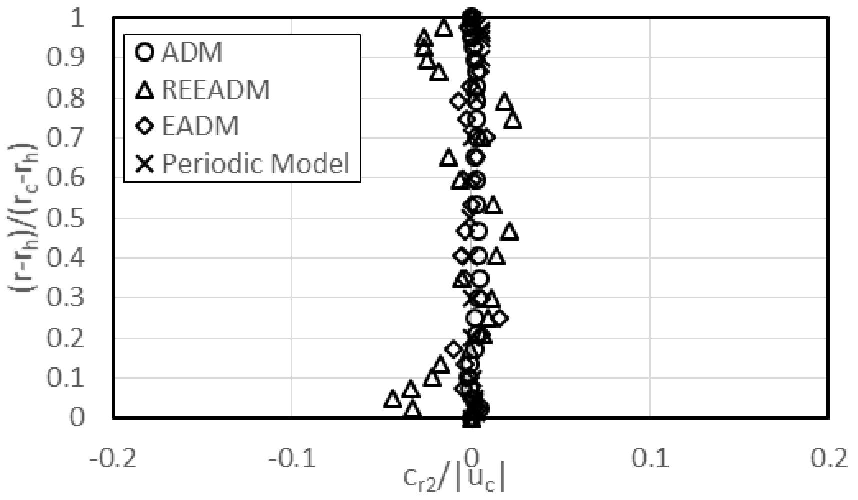


Radial velocity upstream



Radial velocity downstream

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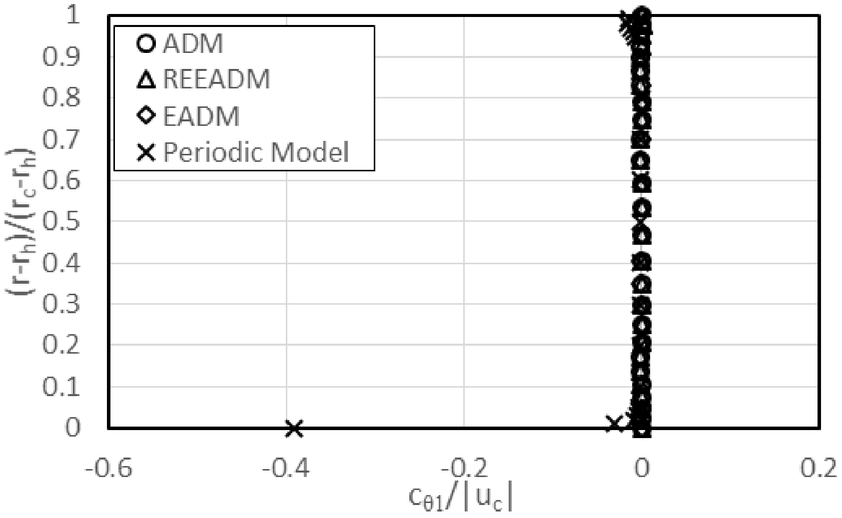
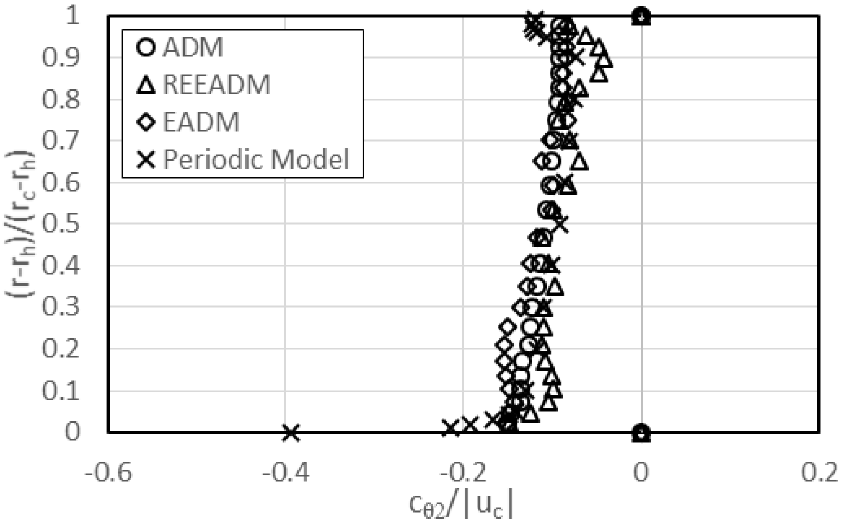
Results Velocity profiles

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



Tangential velocity upstream



Tangential velocity downstream

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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

	P3DM	Actuator disc models
Processors	8 CPUs (2.1-3 GHz)	2 CPUs (3.4 GHz)
RAM	15 Gb	32 Gb
Time	2-28 days	10-120 min

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

- Thiart, G. D., & von Backström, T. W. 1993. Numerical simulation of the flow field near an axial flow fan operating under distorted inflow conditions. *Journal of Wind Engineering and Industrial Aerodynamics*, ***45***(2), pp. 189–214.
- Van der Spuy, S. J., 2011. “Perimeter fan performance in forced draft air-cooled steam condensers”. PhD thesis, University of Stellenbosch.
- Louw, F. G., 2015. “Investigation of the flow field in the vicinity of an axial flow fan during low flow rates”. PhD thesis, University of Stellenbosch.
- Himmelskamp, H., 1947. “Profile investigations on a rotating airscrew”. Phd thesis, University of Göttingen.
- Gur, O., Rosen, A., Propeller performance at low advance ratio, *Journal of Aircraft*, **42**, no. 2, 2005

Thank You

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