Numerical investigation of pressure recovery in an induced draught air-cooled condenser for CSP application

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Background

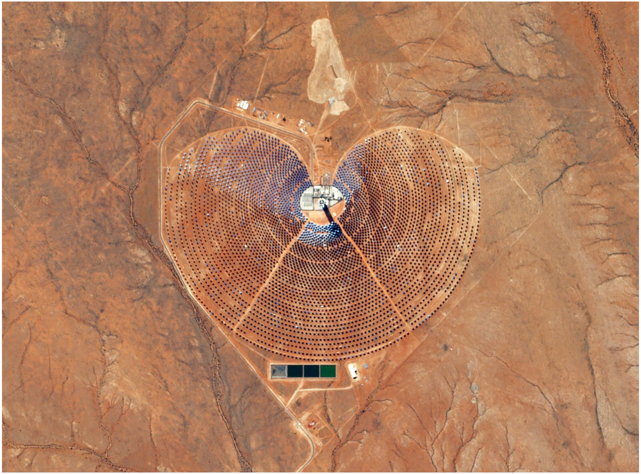

Figure: Khi Solar One

Background

Limited water resources

Figure: Kathu Solar Park

Background

Dry-cooling

Dry-cooling systems are typically employed:

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- Natural draught

Figure: Natural draught

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- Mechanical draught
  - Forced draught
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Figure: Mechanical draught

Figure: Natural draught

Problem statement

- Outlet kinetic energy lost to atmosphere
- This is a system loss
- Decreases the total-to-static efficiency of the fan

Figure: Induced draught air-cooled condensers (ACCs)

Objective

- Minimise the outlet kinetic energy loss of the M-fan

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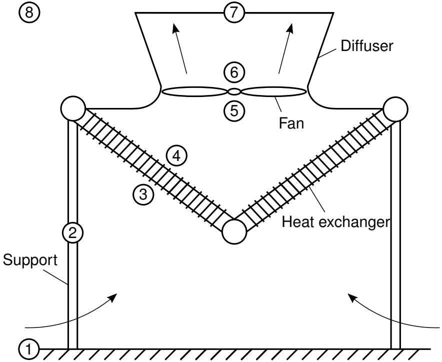
- Minimise the outlet kinetic energy loss of the M-fan
- The M-fan was designed by Wilkinson *et al.* (2017) for CSP application

Table: M-fan specifications

Diameter	24 ft (7.3152 m)
Number of blades	8
Hub-tip-ratio	0.29
Rotational speed	151 rpm
Flow rate	$333\,m^3/s$
Fan static pressure	116.7 Pa

Draught equation

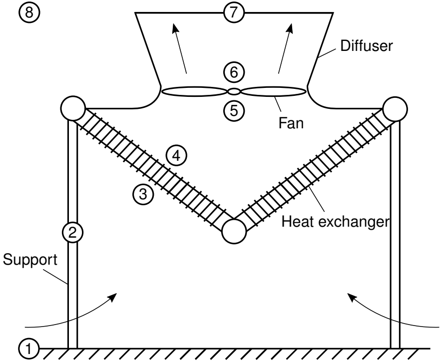
Draught equation:
Energy supplied = energy dissipated



Draught equation:
Energy supplied = energy dissipated

- Dimensionless pressure loss/gain coefficient:

$$K = \frac{\Delta p}{\rho v^2/2}$$



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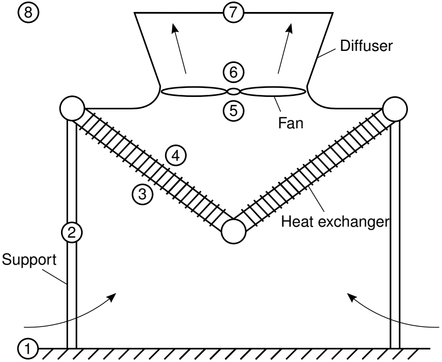

- Induced draught ACC:

$$\Delta p_{\text{Fs}} + \alpha_{e\text{F}} \rho v_{\text{FC}}^2/2 = \Delta p_{\text{sys}} + K_{\text{dif}} \rho v_{\text{FC}}^2/2 + \alpha_{e7} \rho v_7^2/2$$

Pressure recovery

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$$K_{\text{rec}} = \alpha_{e\text{F}} - \alpha_{e7}(A_{\text{FC}}/A_7)^2 - K_{\text{dif}}$$

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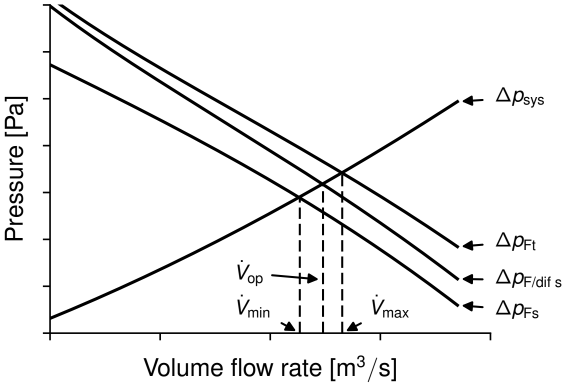
Pressure recovery

Draught equation:

$$\Delta p_{Fs} + K_{rec}\rho v_{FC}^2/2 = \Delta p_{sys}$$

Pressure recovery term:

$$K_{rec} = \alpha_{eF} - \alpha_{e7}(A_{FC}/A_7)^2 - K_{dif}$$



Kinetic energy factor

Pressure recovery

Kinetic energy factor: ratio of actual to mean kinetic energy through a section

$$\begin{aligned}\alpha_{eF} &= \frac{1}{v_{FC}^3 A_{FC}} \int_A c_x \left(c_x^2 + c_\theta^2 + c_r^2 \right) \mathrm{d}A \\ &= \alpha_{eF_x} + \alpha_{eF_\theta} + \alpha_{eF_r}\end{aligned}$$

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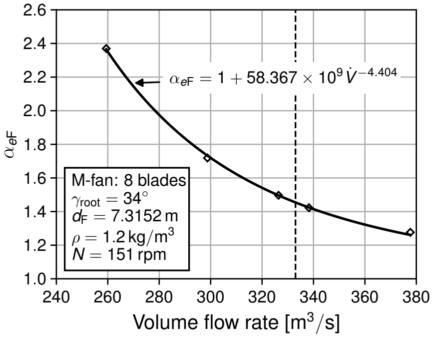

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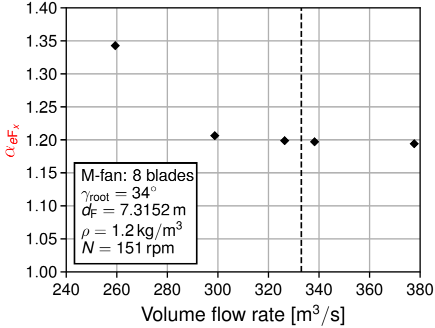

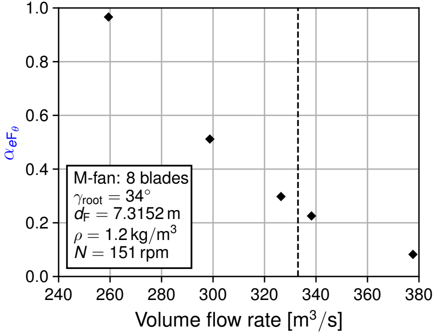

Pressure recovery term:

$$K_{\text{rec}} = \alpha_{e\text{F}} - \alpha_{e7}(A_{\text{FC}}/A_7)^2 - K_{\text{dif}}$$

- Want A_7 as large as possible
- Avoid flow separation

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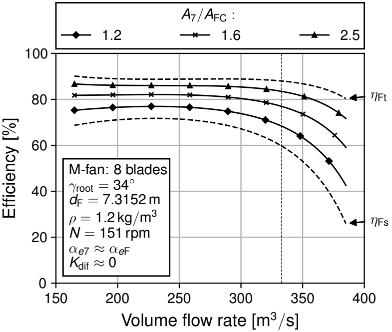

Figure: Efficiency characteristic

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$$K_{\text{rec}} = \alpha_{e\text{F}} - \alpha_{e7}(A_{\text{FC}}/A_7)^2 - K_{\text{dif}}$$

- K_{dif} represents the total pressure loss across the diffuser
- Owing to viscous effects
- Aim to keep as small as possible

Diffuser loss coefficient

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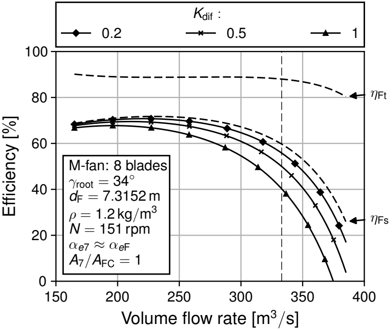

Figure: Efficiency characteristic

Validation case: ERCOFTAC conical diffuser

- Experiments performed by Clausen *et al.* (1993)
- Swirling flow in a conical diffuser
  - Total divergence angle: 20°
  - Area ratio: 2.84

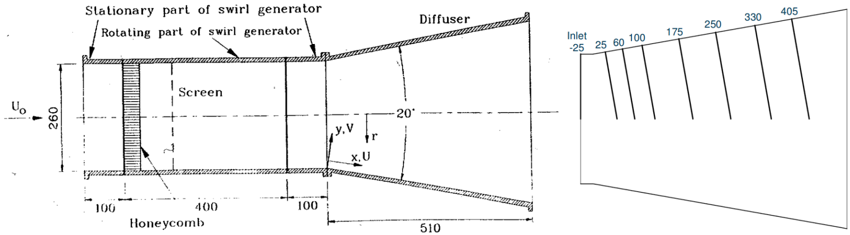

Figure: Experimental setup (Clausen *et al.*, (1993))

Validation case: ERCOFTAC conical diffuser

- Experiments performed by Clausen *et al.* (1993)
- Swirling flow in a conical diffuser
  - Total divergence angle: 20°
  - Area ratio: 2.84
- Swirl sufficient to avoid boundary layer separation
- Swirl insufficient to cause recirculating core flow

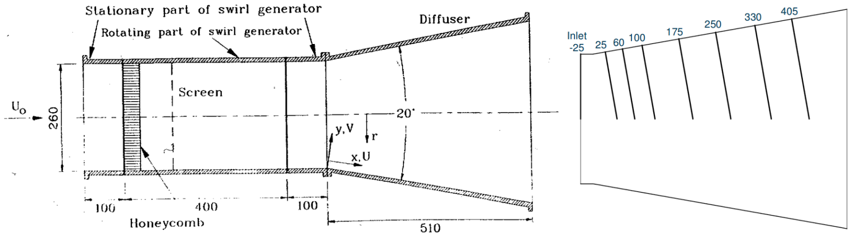

Figure: Experimental setup (Clausen *et al.*, (1993))

- Meshes:
  - Two-dimensional axisymmetric and three-dimensional meshes
  - Outlet extension added: 10 inlet diameters long
  - High-Re turbulence models: $30 < y^+ < 100$
  - Low-Re turbulence models: $y^+ < 5$

Meshing and boundary conditions

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  - Walls: no-slip condition
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Turbulence models

Validation case: ERCOFTAC conical diffuser

Tested six turbulence models:

- High-Re models with wall functions:
  - Standard k–ε (SKE)
  - Realisable k–ε (RKE)
  - SST k–ω (SST)
  - $\overline{v'^2}$–f (V2F)
- Low-Re models with integrated boundary layers:
  - SST k–ω (SSTLR)
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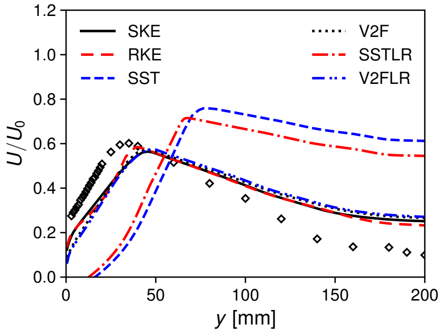


Figure: Streamwise velocity

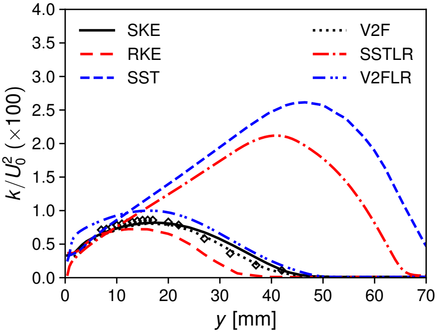
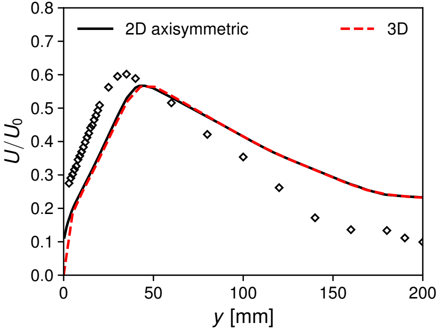


Figure: Turbulent kinetic energy

2D axisymmetric versus 3D simulations

Validation case: ERCOFTAC conical diffuser

- Test axisymmetric assumption
- Used standard k–ε model



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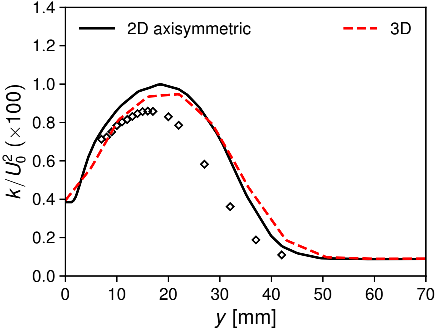

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Full-scale M-fan simulations

- Realisable k–ε model with wall functions
- Two-dimensional axisymmetric mesh

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- Seven configurations to test:
  1. Outlet guide vanes
  2. Conical diffuser
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Full-scale M-fan simulations

- A guide vane with nine blades was designed
- Numerically modelled with the actuator disc model

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Full-scale M-fan simulations

- A guide vane with nine blades was designed
- Numerically modelled with the actuator disc model
- Pressure recovered: 15.9 Pa ($K_{rec} = 0.37$)
- 13.6 % of fan pressure rise at design flow rate

Case 2: Conical diffuser

Full-scale M-fan simulations

- Diffuser length set equal to fan diameter
- Tested different divergence angles to find best diffuser performance

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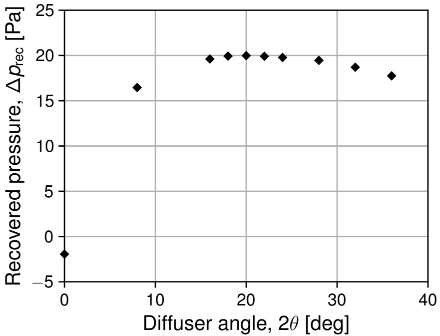
Full-scale M-fan simulations

- Diffuser length set equal to fan diameter
- Tested different divergence angles to find best diffuser performance

- Best angle: $2\theta = 20^\circ$
- Pressure recovered: 20.0 Pa ($K_{\text{rec}} = 0.46$)
- 17.1 % of fan pressure rise at design flow rate



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- Validation study:
  - Two-dimensional axisymmetric simulations
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- M-fan simulations:
  - Swirl removal: 13.6 % pressure increase
  - Conical diffuser with 20° divergence angle: 17.1 % pressure increase