CFD OF AIR FLOW IN HYDRO POWER GENERATORS

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2010-12-17

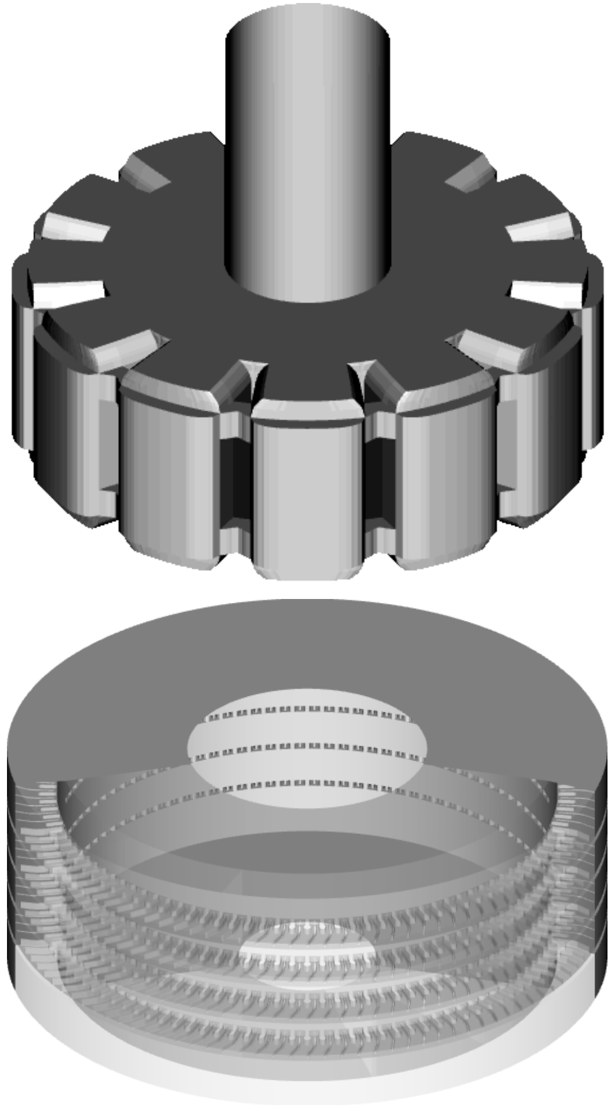
Problem Definition

- Half of the electricity generation in Sweden from hydroelectric power generation
- Modifications to the existing units → significant contributions to the total energy production
- Increased power output → more heat to be removed
- Two large sources of energy losses in the generators: thermal and ventilation losses
  - The electric resistance in the generator coils → heat to be removed
  - Air cooling of the rotor and the stator → ventilation losses
- The stator should be cooled by air flowing through the stator air channels
- Focus of the present work: axially cooled generators

Generator

- Rotor - The rotating part:
  - Magnetic poles with coils
  - Driven by the turbine
- Stator - The stationary part:
  - Windings
  - Cooling channels

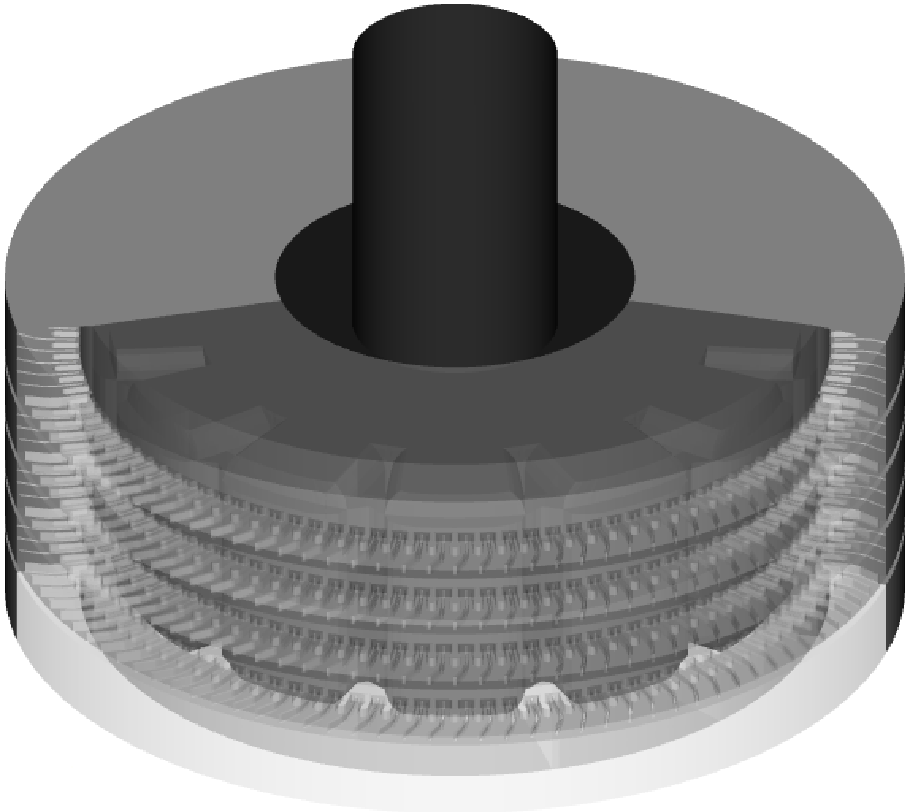
The electric current is induced in the stator windings by the relative motion of the rotor poles



Case study

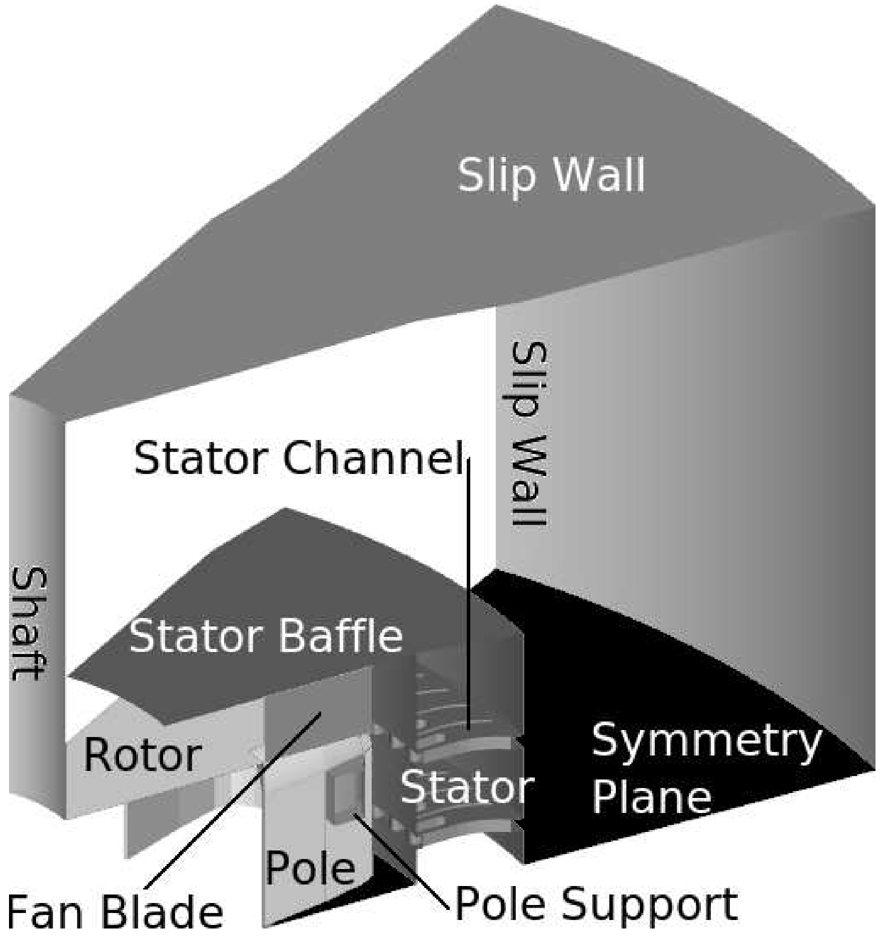
Generator at Uppsala University (SVANTE)

- Previously an electric motor
- 4 axial rows of stator cooling channels
- 108 cooling channels in each row
- 12 rotor poles
- Rotational speed: 500 rpm
- Inner radius of the stator: 36.5 cm
- Outer radius of the stator: 43.7 cm

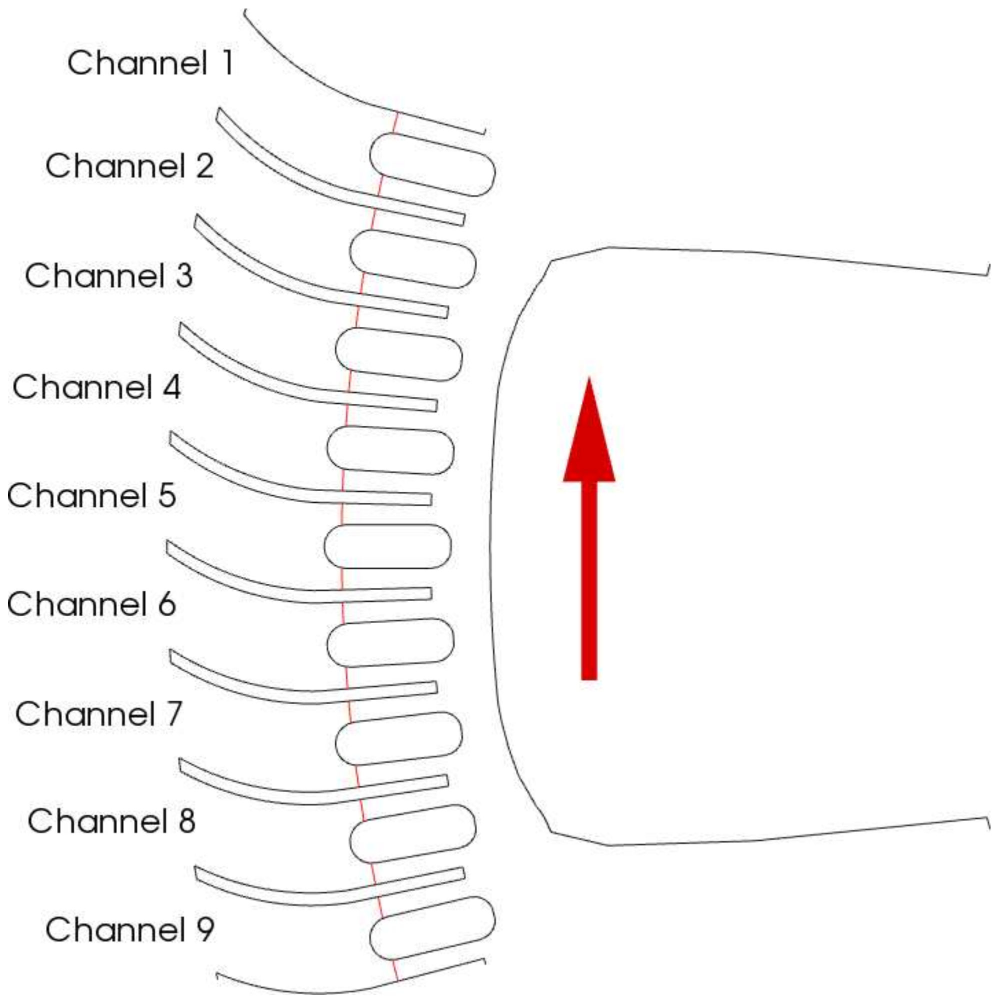


Geometry in OpenFOAM

- A 1/12 sector in the tangential direction
- Symmetri-plane in the middle
- 2 channel rows
- 9 channels in each row
- 1 pole
- Low-Re Launder-Sharma turbulence model
- No inlet and outlet boundaries
  → no prescribed mass flow
- Air recirculating in an extra space
  → computed mass flow



Stator cooling channels



Cases

- Frozen rotor concept: MRFSimpleFOAM (MRF = Multiple Reference Frames)

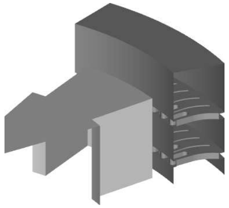
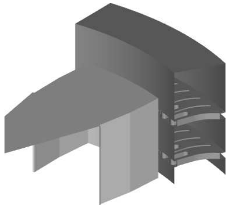
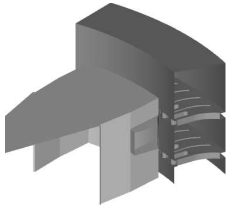
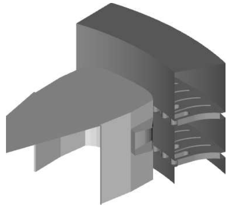
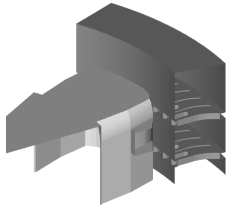
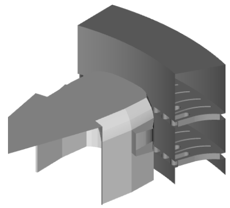
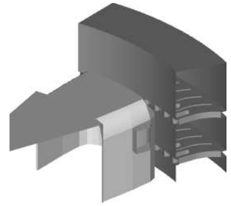
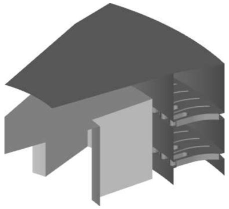
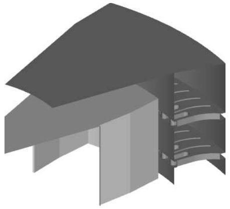
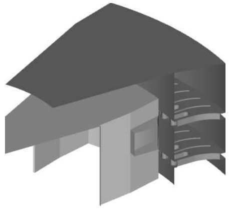
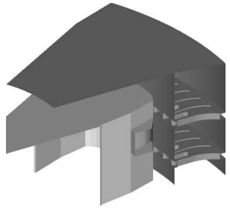
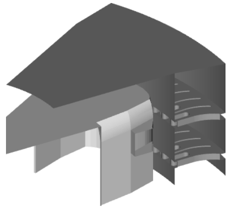
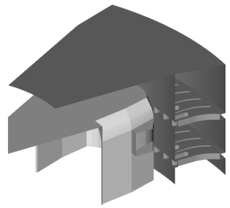
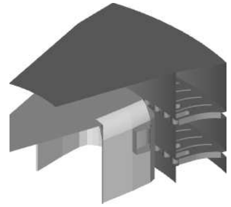
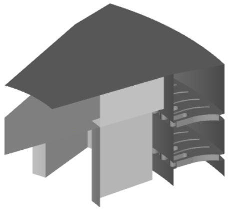
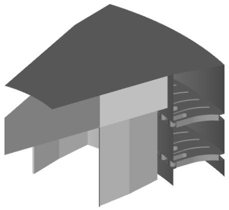
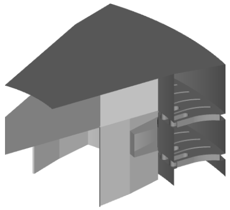
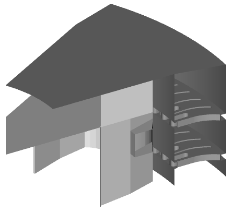
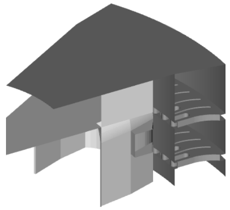
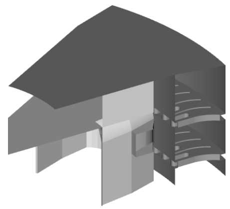
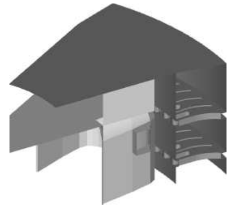
$$\frac{\partial \vec{u_I}}{\partial t} + \nabla \cdot (\vec{u_R} \otimes \vec{u_I}) + \vec{\Omega} \times \vec{u_I} = -\nabla(p/\rho) + \nu \nabla \cdot \nabla(\vec{u_I})$$
$$\nabla \cdot \vec{u_I} = 0$$

- Low-Re Launder-Sharma turbulence model

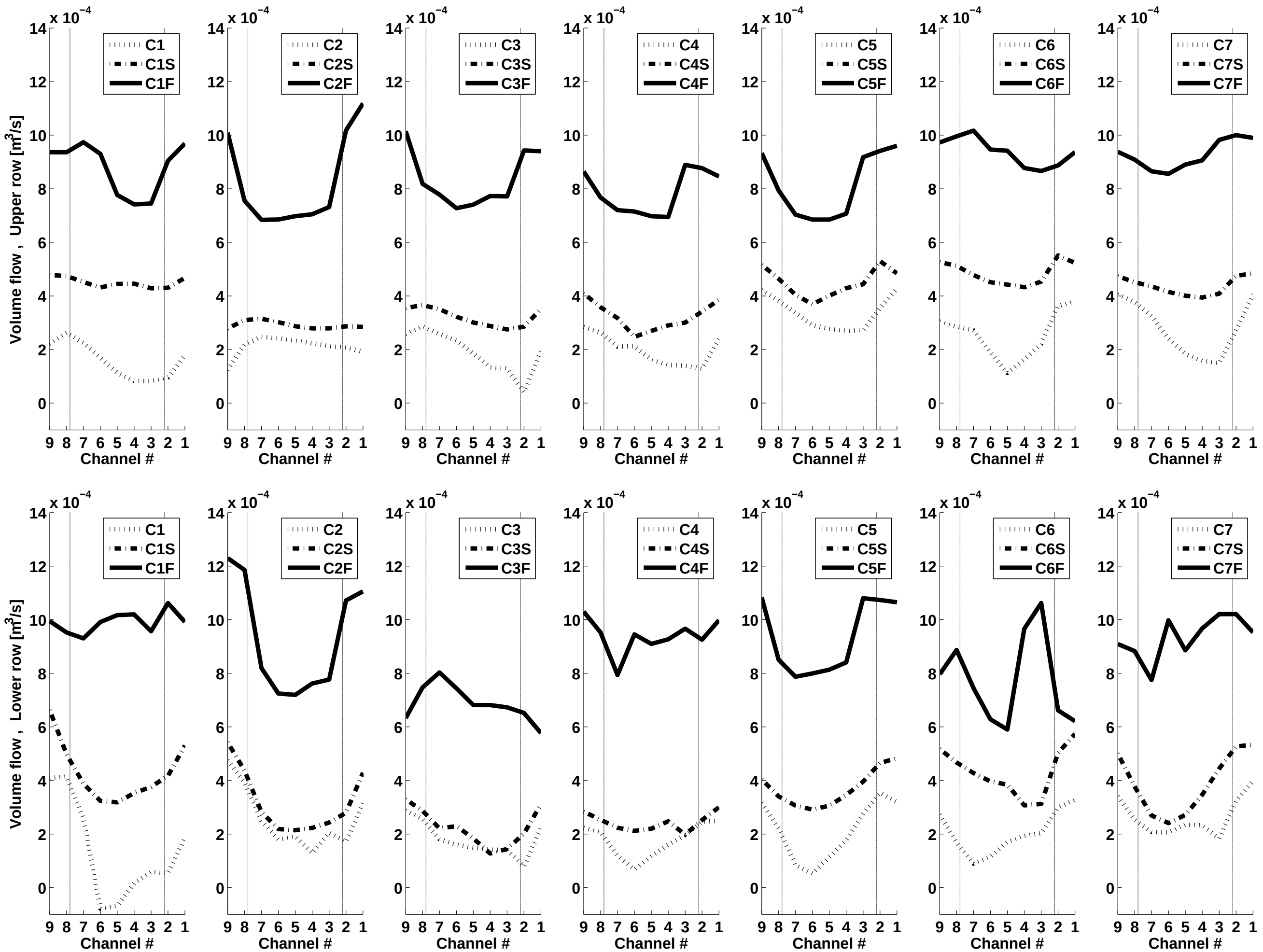
$$\frac{\partial k}{\partial t} + \nabla \cdot (Uk) - \nabla \cdot D_{k,eff} \nabla k = G - (\tilde{\varepsilon} + D)$$
$$\frac{\partial \tilde{\varepsilon}}{\partial t} + \nabla \cdot (U\tilde{\varepsilon}) - \nabla \cdot D_{\varepsilon,eff} \nabla \tilde{\varepsilon} = C_{\varepsilon 1} G \frac{\tilde{\varepsilon}}{k} - C_{\varepsilon 2} f_2 \frac{\tilde{\varepsilon}^2}{k} + E$$

- Mesh generated with blockMesh (parameterized m4 script)
- A total of 21 cases: 7 rotor designs, each with
  - a base stator, $C\#$
  - a baffled stator, $C\#S$
  - a baffled stator and fan blades on the rotor, $C\#F$

Pole and stator design in all test cases

	Pole design 1-7						
$C\#$	C1 	C2 	C3 	C4 	C5 	C6 	C7 
$C\#S$	C1S 	C2S 	C3S 	C4S 	C5S 	C6S 	C7S 
$C\#F$	C1F 	C2F 	C3F 	C4F 	C5F 	C6F 	C7F 

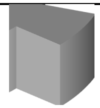
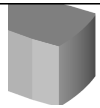
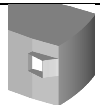
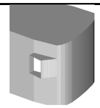
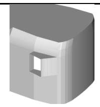
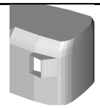
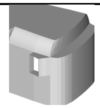
Volume Flow Distributions



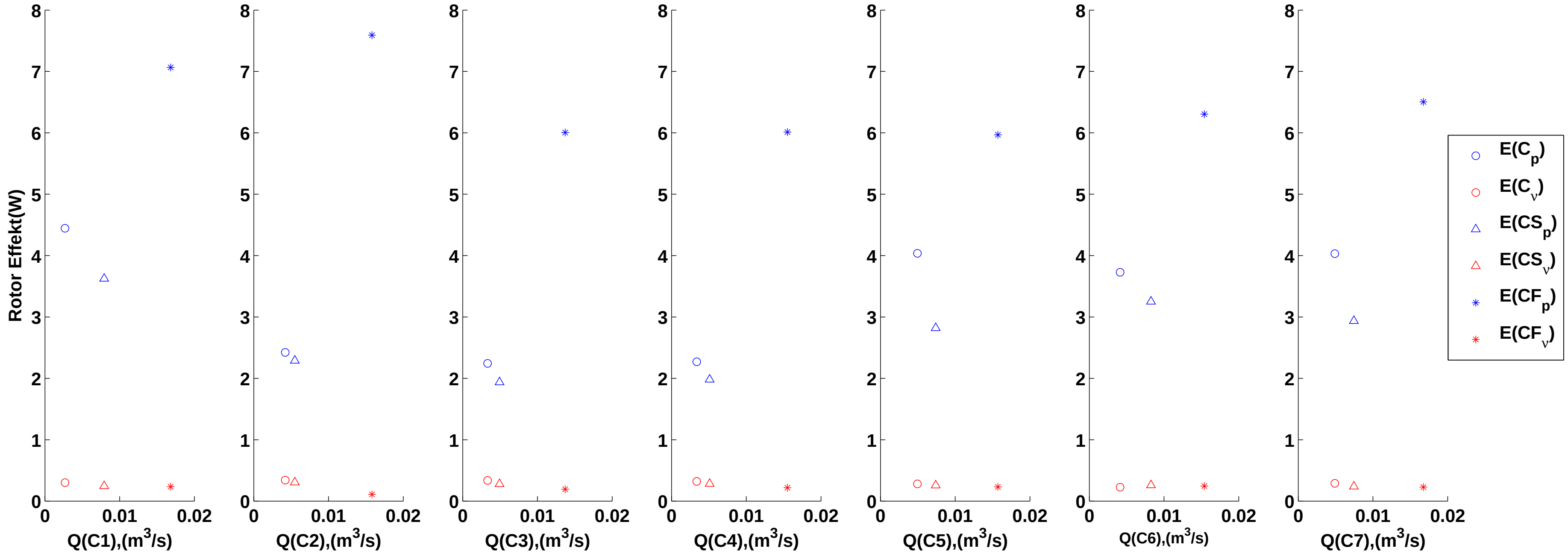
Remarsk About Volume Flow Distributions

- Volume flows:
  - smallest in cases without stator baffles, $C\#$
  - largest in cases with both stator baffles and fan blades, $C\#F$
- $C1 \rightarrow$ negative volume flows $\rightarrow$ air sucked in the channels from outside the stator

Case Specifications and Rotor Axial Power

Case name	Pole design	remarks	Rotor axial power (W) ($\dot{E} = \dot{E}_{press} + \dot{E}_{visc}$)					
			Base Case		Stator Baffle		Fan Blade	
			$\dot{E}_{press}$	$\dot{E}_{visc}$	$\dot{E}_{press}$	$\dot{E}_{visc}$	$\dot{E}_{press}$	$\dot{E}_{visc}$
C1			4.45	0.30	3.62	0.25	7.07	0.24
C2		Reduced areas	2.42	0.34	2.29	0.31	7.59	0.11
C3		Pole supports	2.24	0.34	1.94	0.28	6.00	0.19
C4		Rounded pole front	2.27	0.32	1.98	0.28	6.01	0.22
C5		Rounded pole edges	4.04	0.28	2.82	0.26	5.97	0.23
C6		More rounded pole edges	3.73	0.23	3.25	0.26	6.30	0.25
C7		Half planned top front	4.03	0.29	2.94	0.24	6.50	0.23

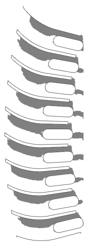
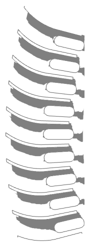
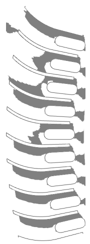
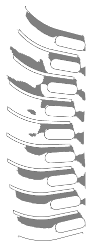
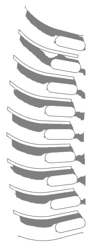
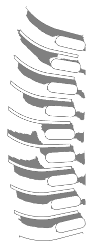
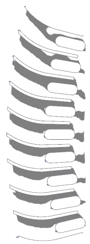
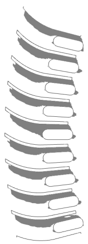
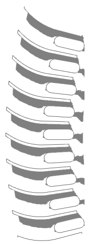
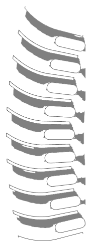
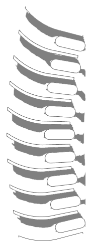
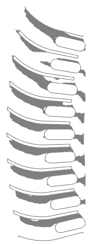
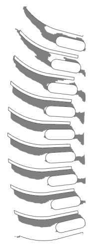
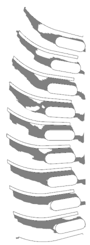
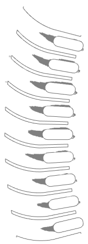
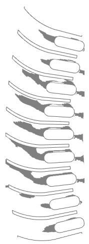
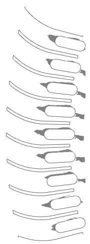
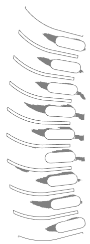
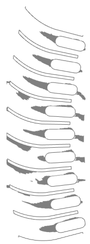
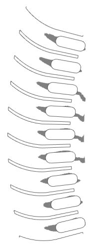
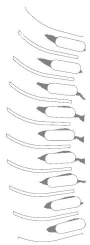
Rotor axial Power vs volume flow



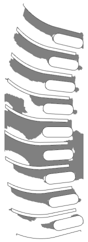
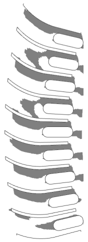
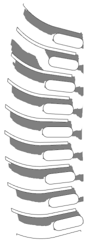
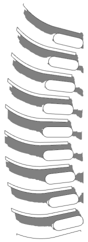
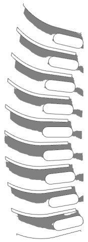
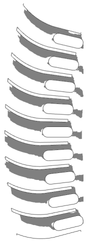
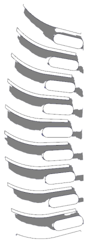
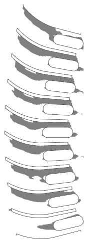
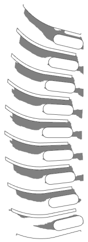
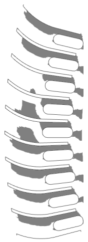
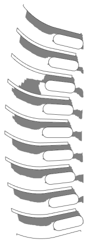
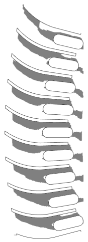
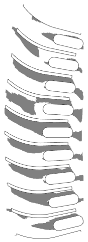
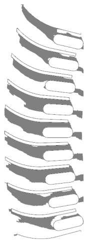
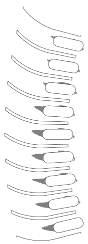
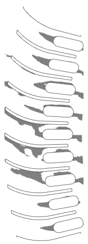
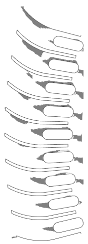
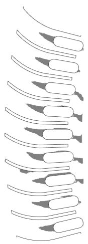
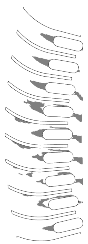
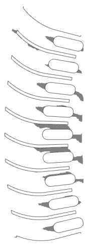
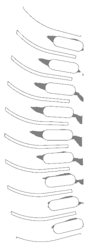
Remarks About Rotor Axial Power

- The rotor power divided into:
  - viscous part, $\dot{E}_{visc}$
  - pressure part, $\dot{E}_{press}$
- $\dot{E}_{press} >> \dot{E}_{visc}$
- $C\#$ requiring more axial power than $C\#S$ (larger volume flows) $\rightarrow$ The stator baffles reduce the losses
- The highest rotor axial power required by $C\#F$

Recirculation Zones in the Upper Stator Channels

	Pole design 1-7						
$C\#$	C1 	C2 	C3 	C4 	C5 	C6 	C7 
$C\#S$	C1S 	C2S 	C3S 	C4S 	C5S 	C6S 	C7S 
$C\#F$	C1F 	C2F 	C3F 	C4F 	C5F 	C6F 	C7F 

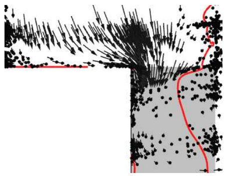
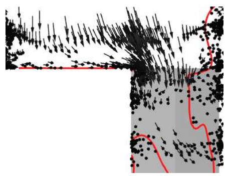
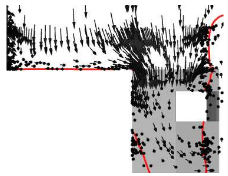
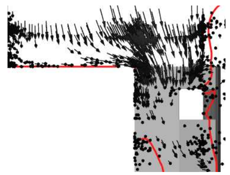
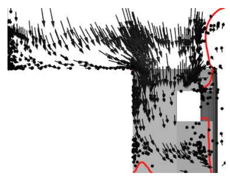
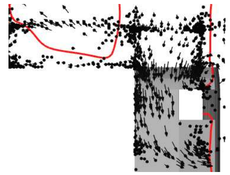
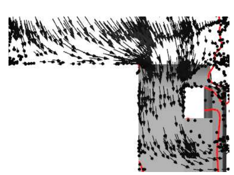
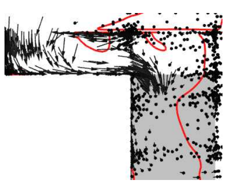
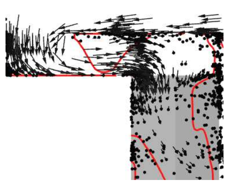
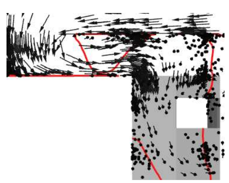
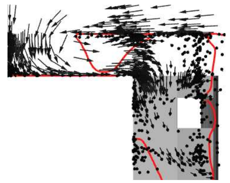
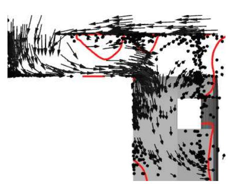
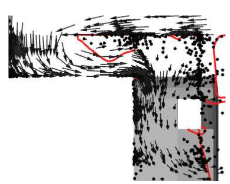
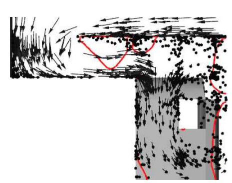
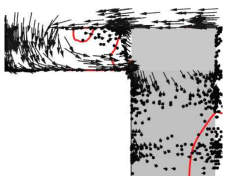
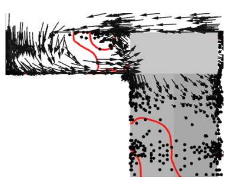
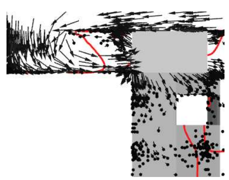
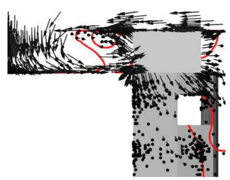
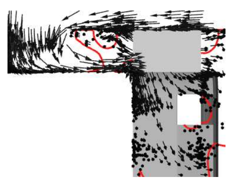
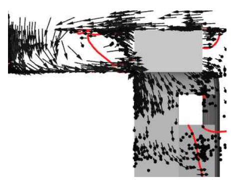
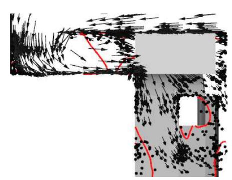
Recirculation Zones in the Lower Stator Channels

	Pole design 1-7						
C#	C1 	C2 	C3 	C4 	C5 	C6 	C7 
C#S	C1S 	C2S 	C3S 	C4S 	C5S 	C6S 	C7S 
C#F	C1F 	C2F 	C3F 	C4F 	C5F 	C6F 	C7F 

Remarks About Recirculation Zones in the Stator Channels

- The shaded areas show the recirculation zones in the stator channels
- Cases without fan blades:
  - a large recirculation zone at the downstream of the stator windings
  - air sucked in from one side of the stator windings and pushed out from the other side
- Cases with fan blades:
  - considerably smaller recirculation zones
  - air sucked in the from both sides, caused by the large pressure build-up

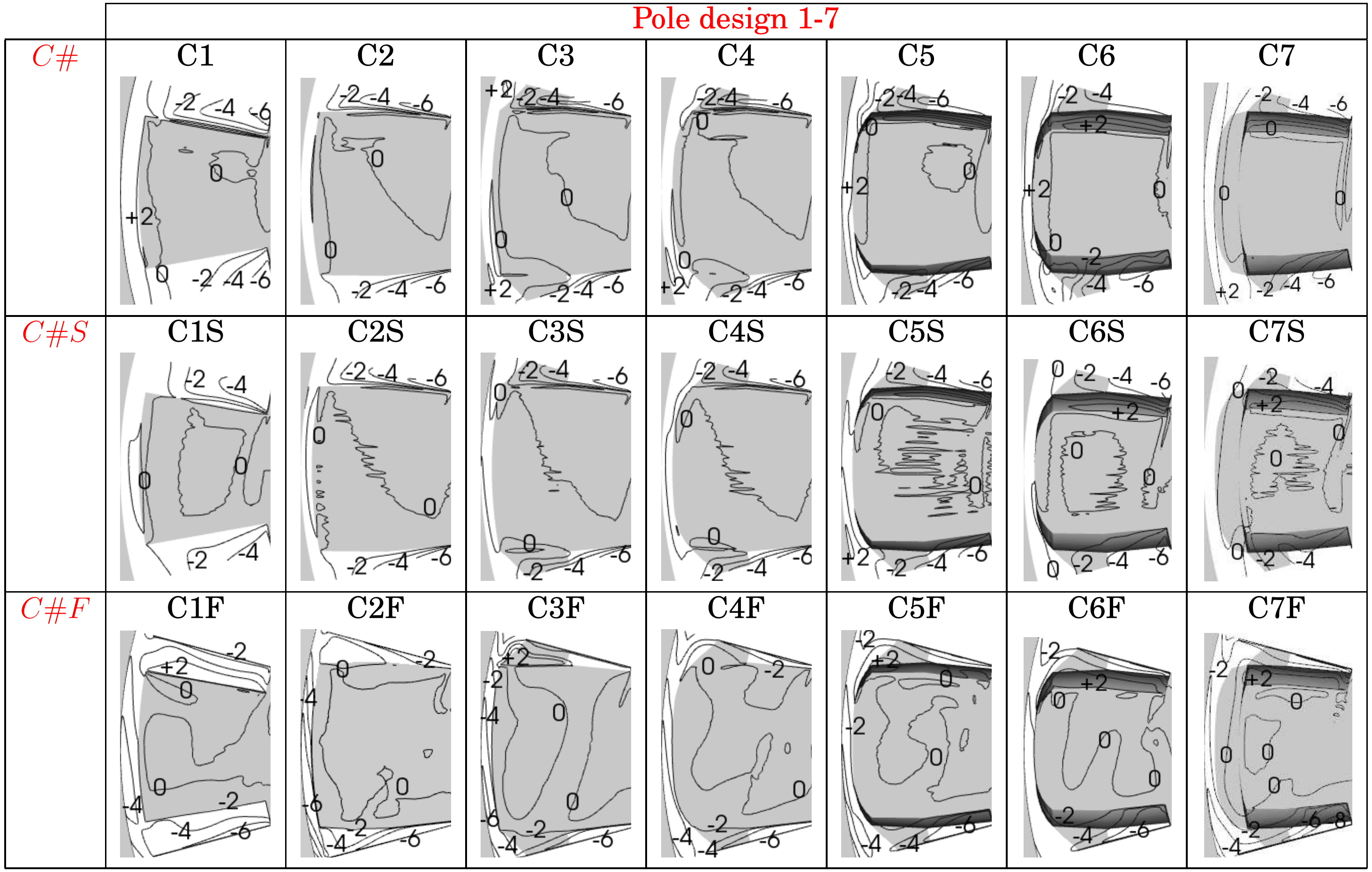
Unit Vectors of the Flow Between the Poles, $(\vec{V}/|\vec{V}|)$

	Pole design 1-7						
$C\#$	C1 	C2 	C3 	C4 	C5 	C6 	C7 
$C\#S$	C1S 	C2S 	C3S 	C4S 	C5S 	C6S 	C7S 
$C\#F$	C1F 	C2F 	C3F 	C4F 	C5F 	C6F 	C7F 

Remarks About Unit Vectors of the Flow Between the Poles

- Thin red curves showing the regions with 0-axial velocity
- Regions of upward velocities near the stator inner wall
  → impossible to use boundary conditions at the inlet
  → not desirable
- Stator baffles:
  - separation just under the edge of the baffle
  - purely downward velocities at the inlet to the machine
- Fan blades:
  - strong pressure build up
    → driving the flow more downwards
    → reducing the regions with upward velocities
  - minimizing separation region under the stator baffle

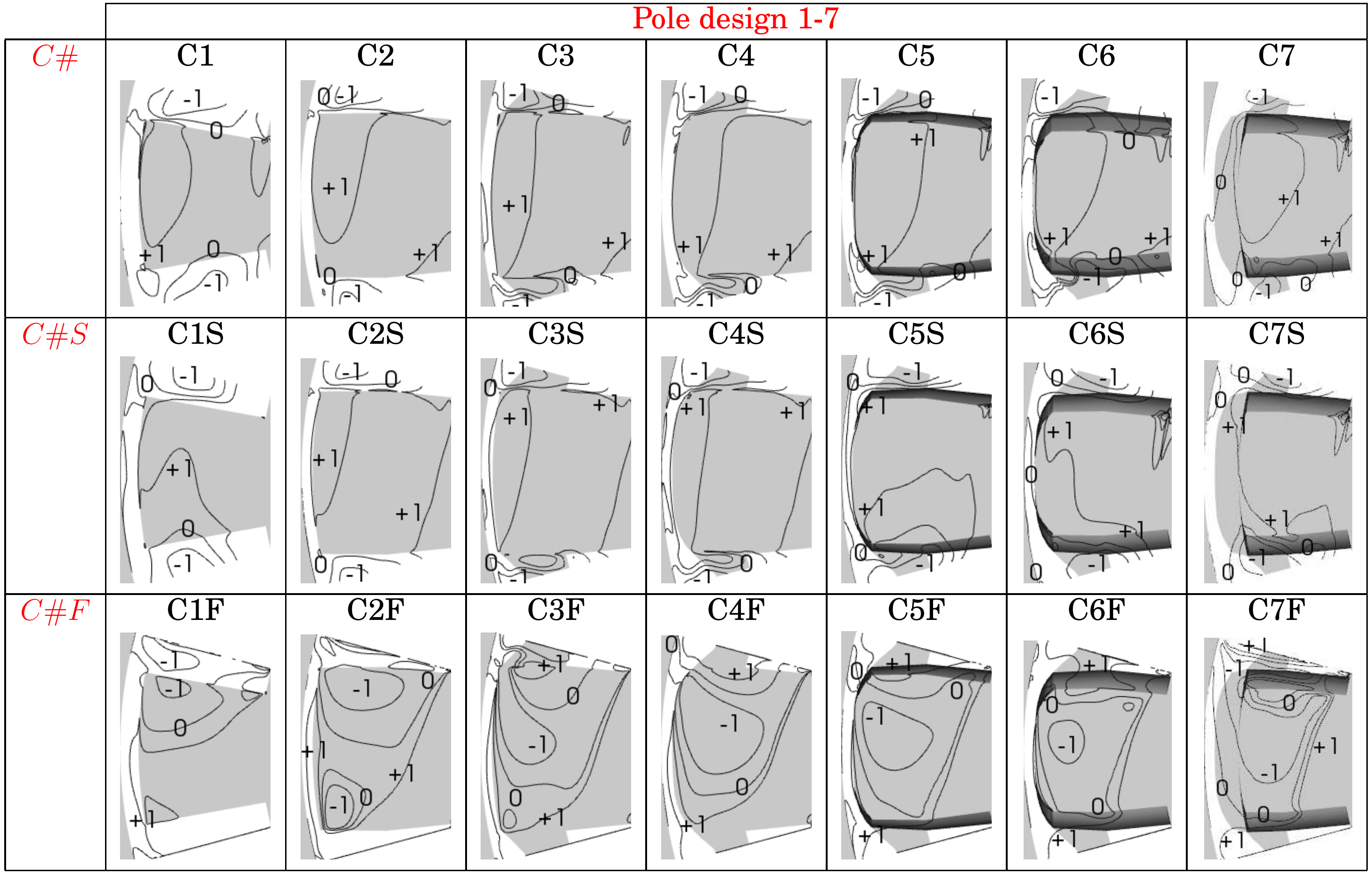
Contour Lines of Axial Velocity $0.2mm$ Above the Pole



Remarks About Axial Velocity Above the Pole

- The axial velocities shown in the boundary layer region just above the poles
- Positive sign → upward velocities → not desirable
- Upward velocity regions in the air gap between The rotor and the stator
- Stator baffle
  - weaker upward velocities near the rotor pole (larger pressure build-up)
- Fan blades
  - reducing the upward velocities even more (even larger pressure build-up) → higher volume flows

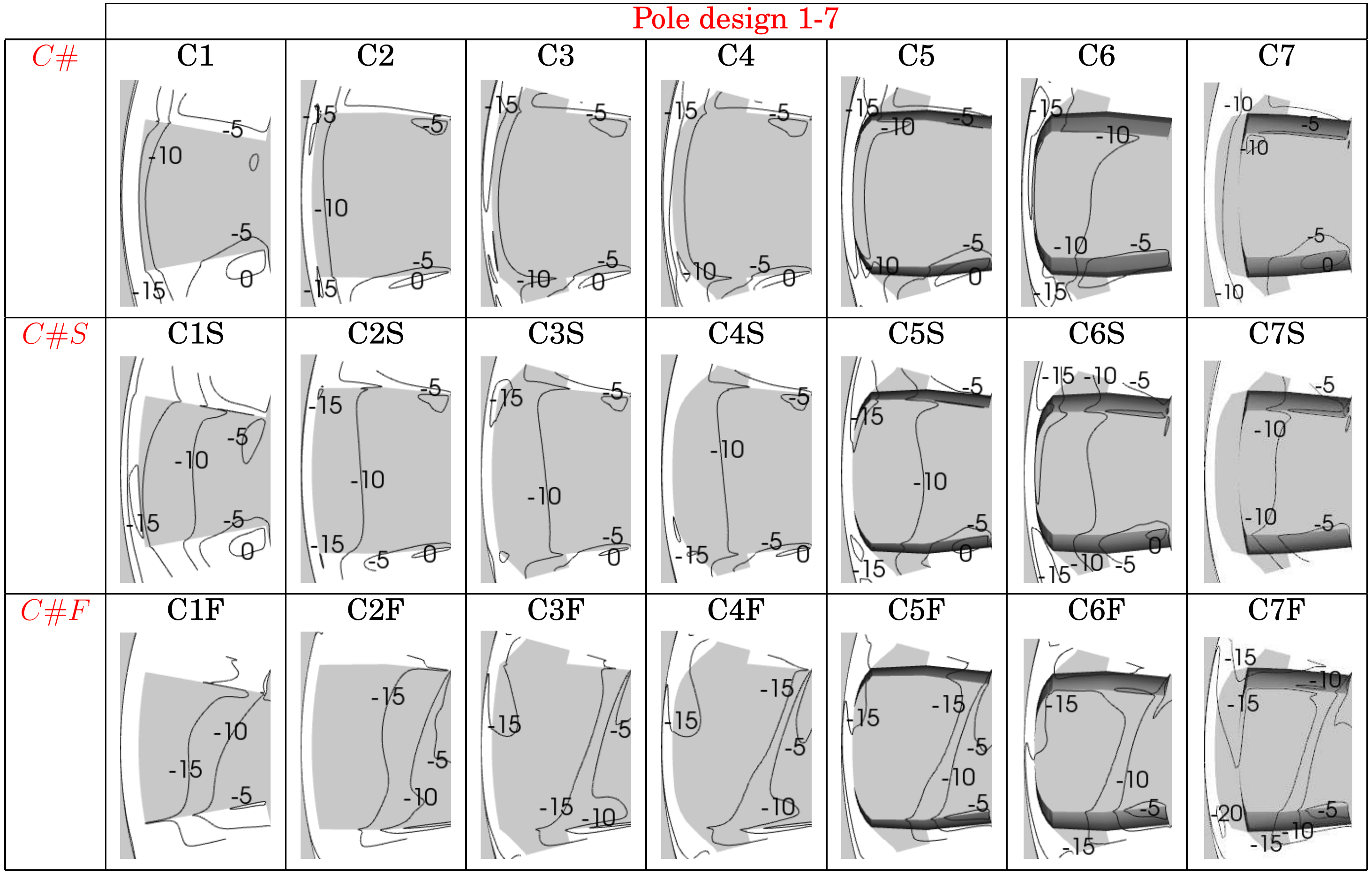
Contour Lines of Radial Velocity $0.2mm$ Above the Pole



Remarks About Radial Velocity Above the Pole

- The radial velocities shown in the boundary layer region just above the pole
- Negative radial velocities in the gap between the rotor and the stator
  $\rightarrow$ recirculation area between the poles
- Cases with fan blades
  $\rightarrow$ recirculation area between the fan blades

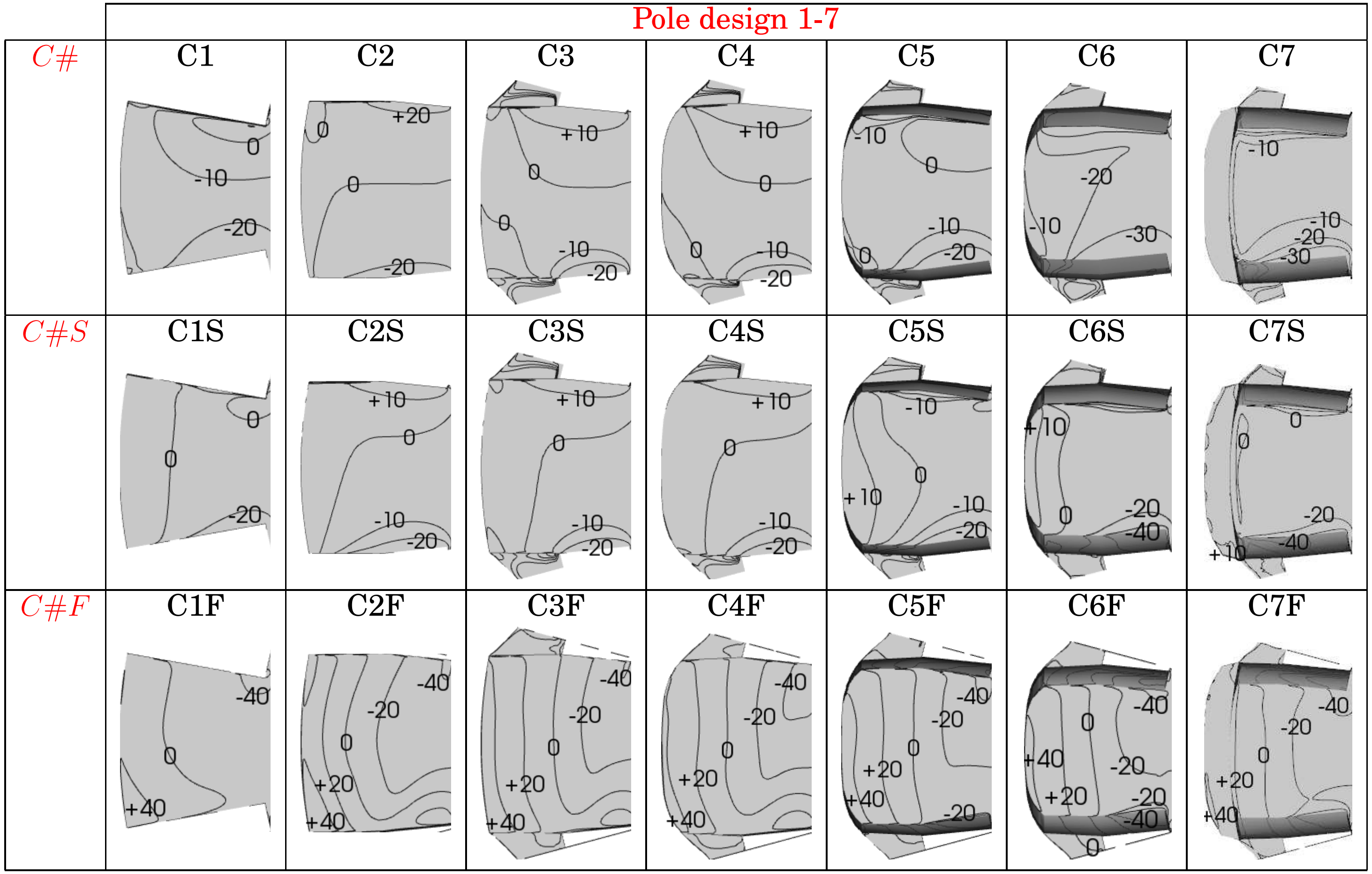
Contour Lines of tangential Velocity $0.2mm$ Above the Pole



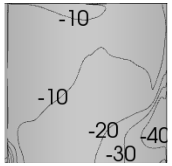
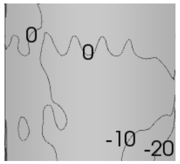
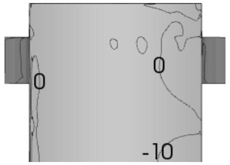
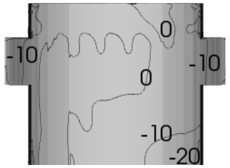
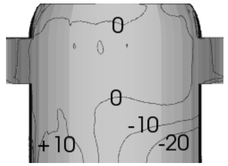
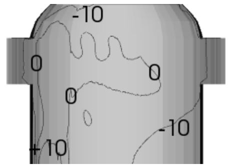
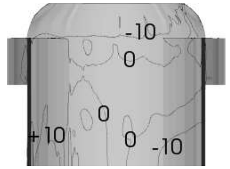
Remarks About Tangential Velocity Above the Pole

- Tangential velocities shown in the boundary layer region just above the pole
- Negative sign → clockwise rotation in the picture
- Stator baffle
  - increased tangential velocitiez
- Fan blades
  - largest tangential velocities
- Rounding the pole edges
  - larger tangential velocities above the rotor

Contour Lines of $(\frac{p_{stat}-p_{stat,ref}}{\rho})$ on Topf of the Pole



Contour Lines of $(\frac{p_{stat}-p_{stat,ref}}{\rho})$ on the Front Side of the Pole

	Pole design 1-7						
	C1	C2	C3	C4	C5	C6	C7
C#							
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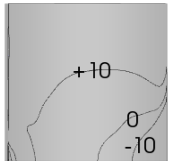
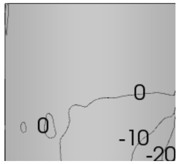
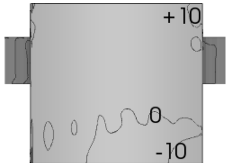
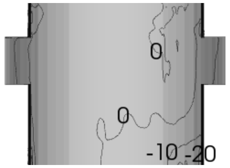
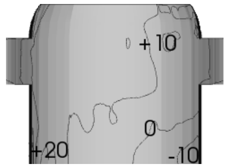
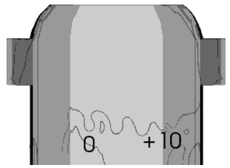
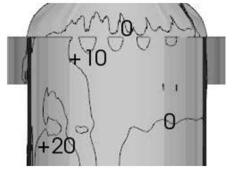
C#S							
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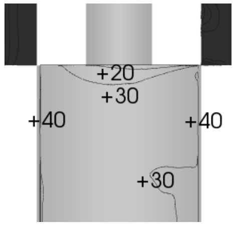
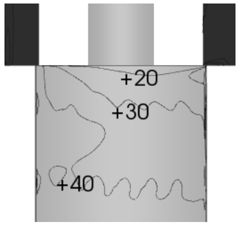
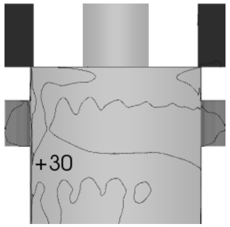
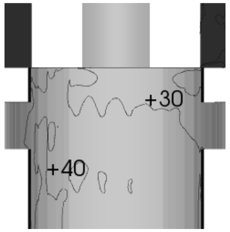
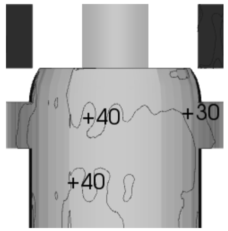
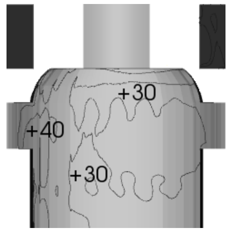
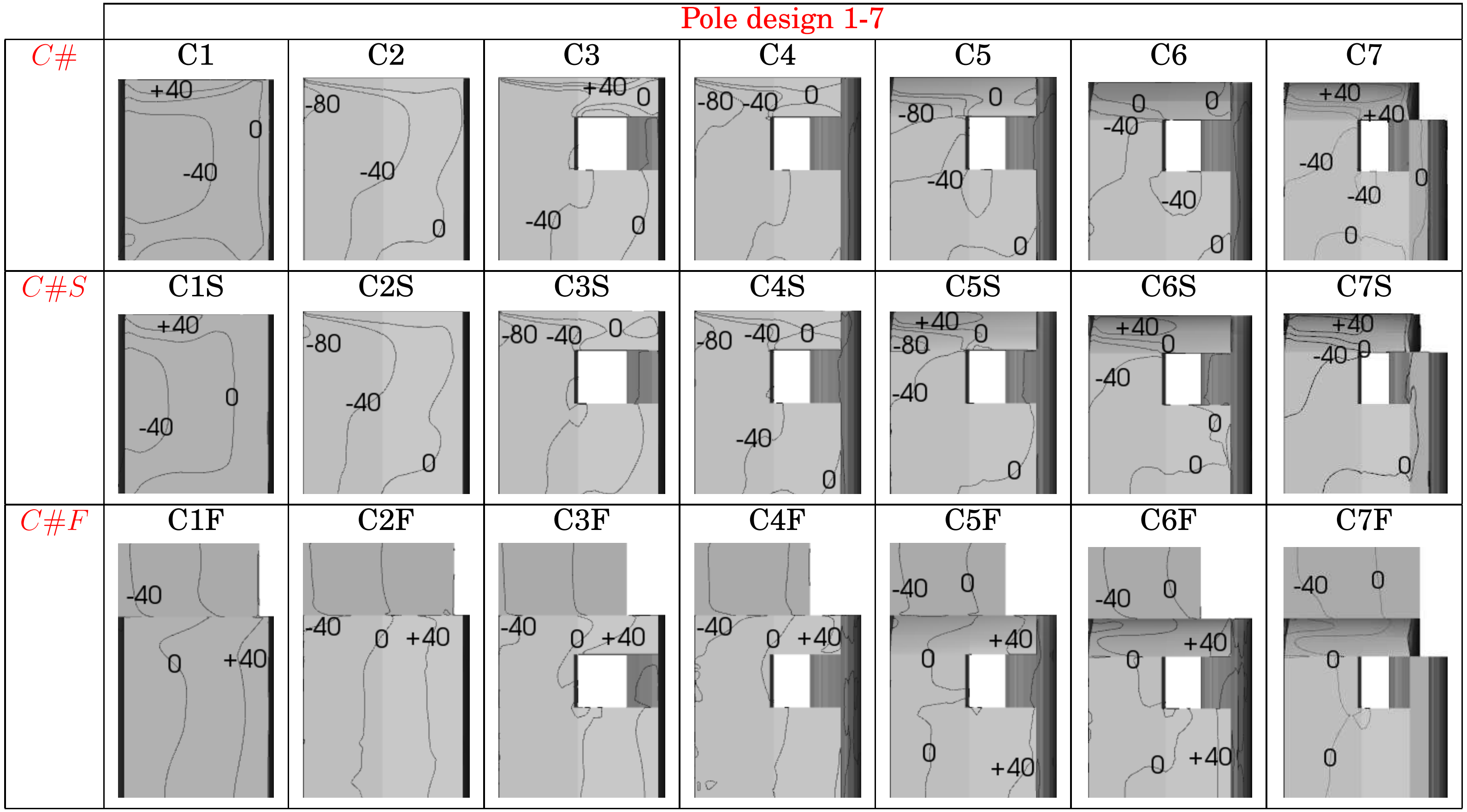
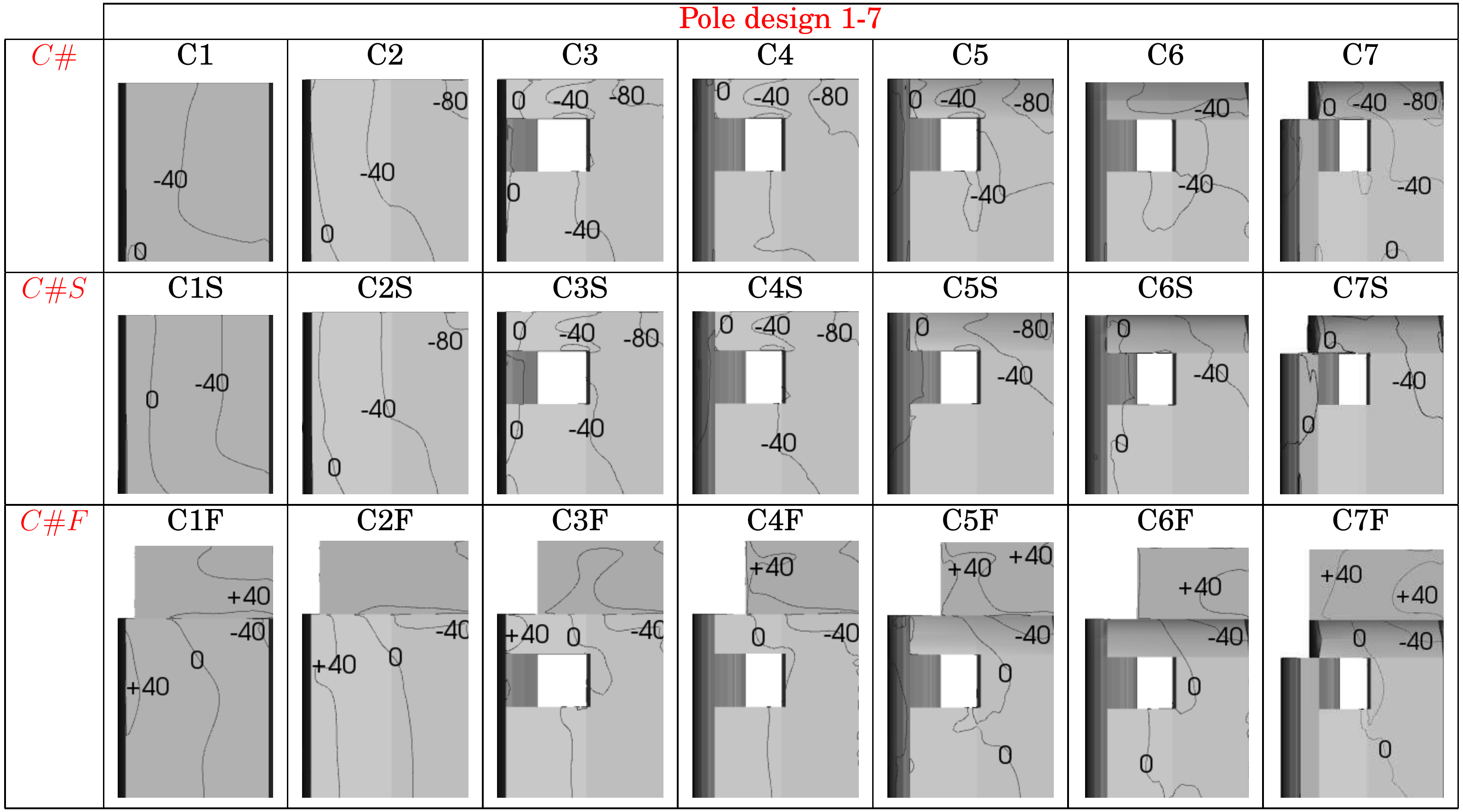
C#F							

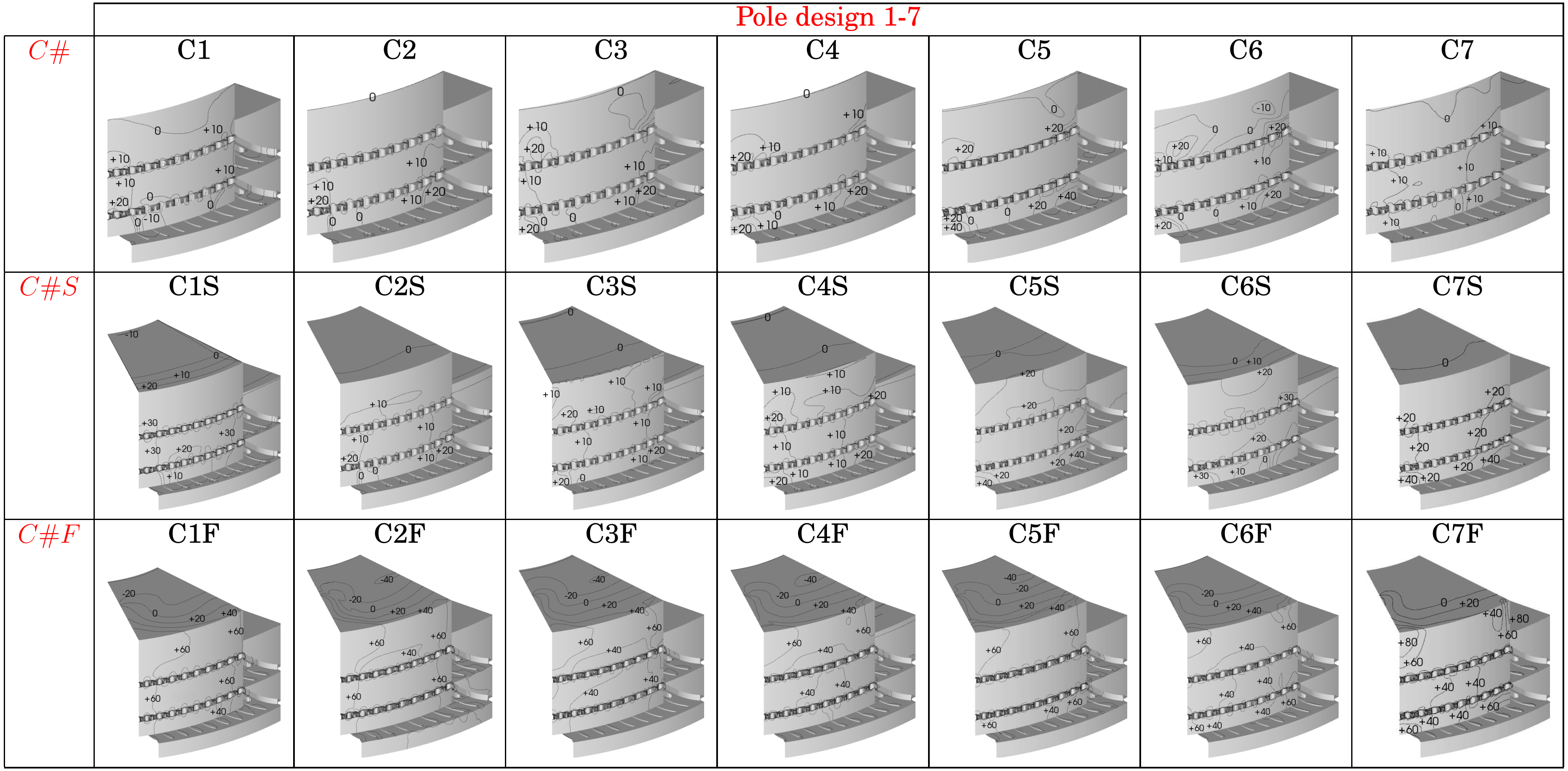
Contour Lines of $\left(\frac{p_{stat}-p_{stat,ref}}{\rho}\right)$ on the Pole Pressure Side



Contour Lines of $\left(\frac{p_{stat} - p_{stat,ref}}{\rho}\right)$ on the Pole Suction Side



Contour Lines of $\left(\frac{p_{stat}-p_{stat,ref}}{\rho}\right)$ Inside the Stator



Remarks About Pressure Distributions

- The quantities p_{stat}, $p_{stat,ref}$ and ρ refering to the static pressure in each cell, static pressure in a reference cell, and density
- The contour lines plotted with respect to the reference values in a reference cell (same position in all cases)
- Lower ($\frac{p_{stat}-p_{stat,ref}}{\rho}$) near the rotor body
  $\rightarrow$ lower static pressure
  $\rightarrow$ stronger suction near the rotor body

Conclusions

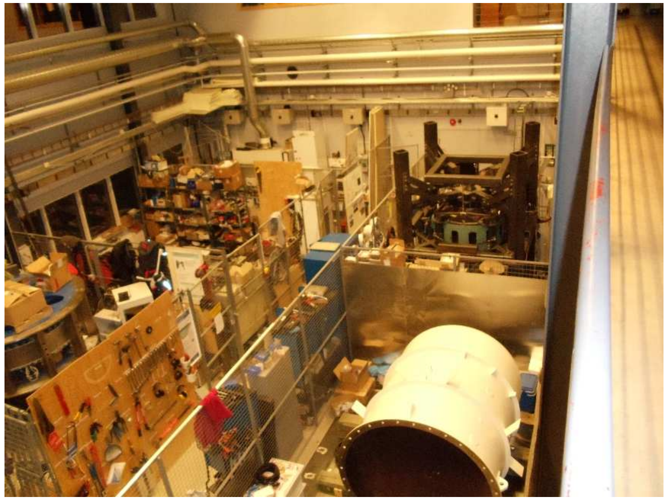
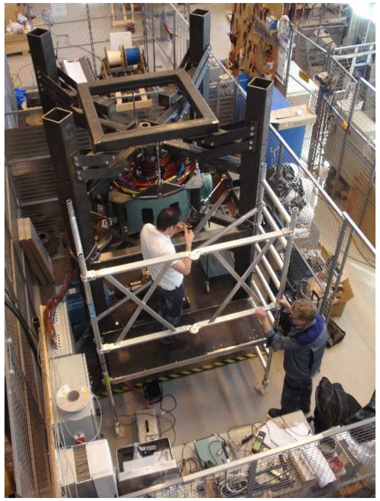
- Complex flow
  - non-uniform
  - separation
  - recirculation
- Stator baffles
  - increasing volume flow
  - eliminating outward flow at the inlet
  - reducing losses
- Rotor fan blades and stator baffles
  - increasing volume flow
  - minimizing recirculation in the channels
  - high rotor axial power required

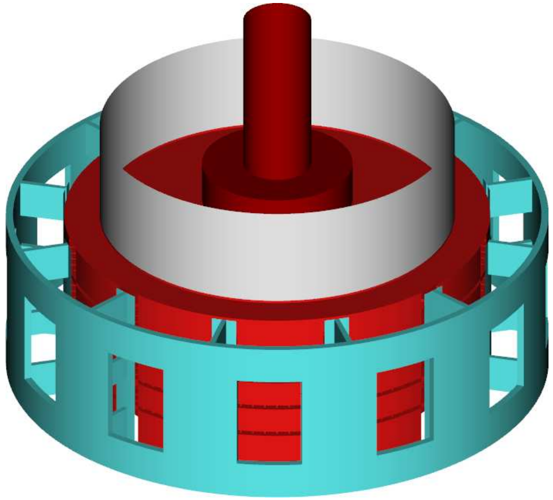
Parallel projects

- Incompressible RAS turbulence models in OpenFOAM-1.5.x
  - models investigated
  - implementations compared to the original models
  - results verified in a backward-facing step case and compared to the experimental results
  - led to the choice of Launder-Sharma $k - \varepsilon$ model
- Laminar couette flow
  - velocity and pressure distributions compared to the analytical resutls

Future Work

- Measurements at Uppsala University
- Modifications to the geometry
- Building a rig at CHALMERS
- Running unsteady simulations with mesh motion



Thank you!