The Design of a Family of Process Compressor Stages

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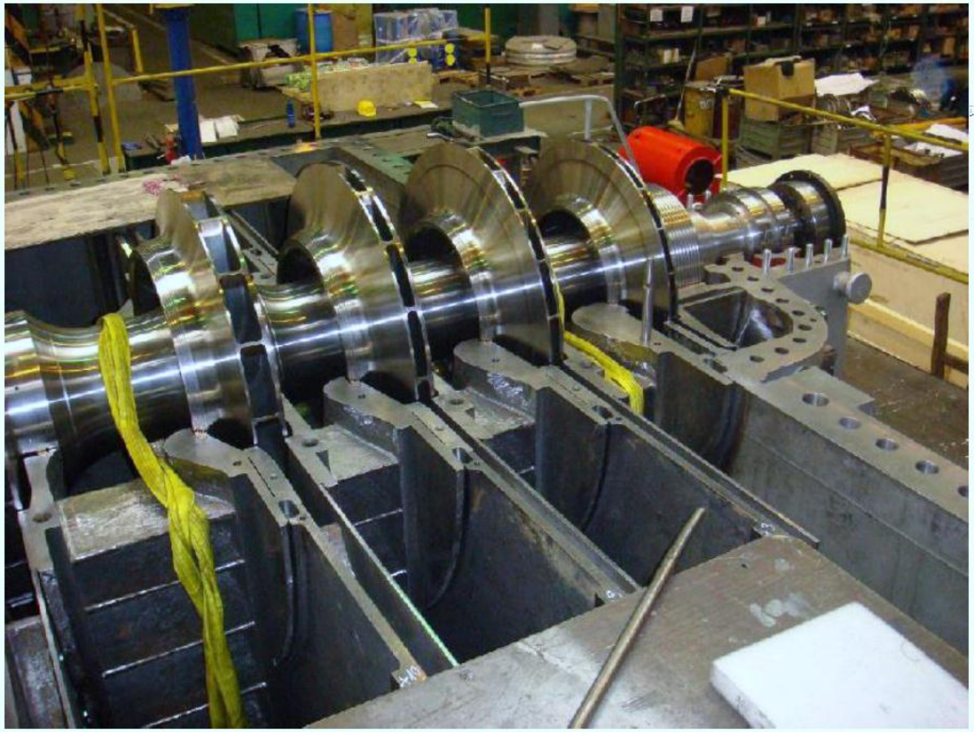
Outline

- Objectives
- Master and Derived Stages
- 1D Design Guidelines
- Detailed design
- Manufacture and Testing
- Summary

Multistage inline compressors

- Used in a wide range of volume flows, pressure ratios and gas properties for different applications
- Use families of pre-engineered stages to meet individual customer's requirements by changing
  - Impeller diameter
  - Number of stages
  - Stage types
  - Speed
  - Cooling arrangement
- Overall performance is calculated by stage-stacking of the individual stage characteristics
- Penalties for 'failure' quite high



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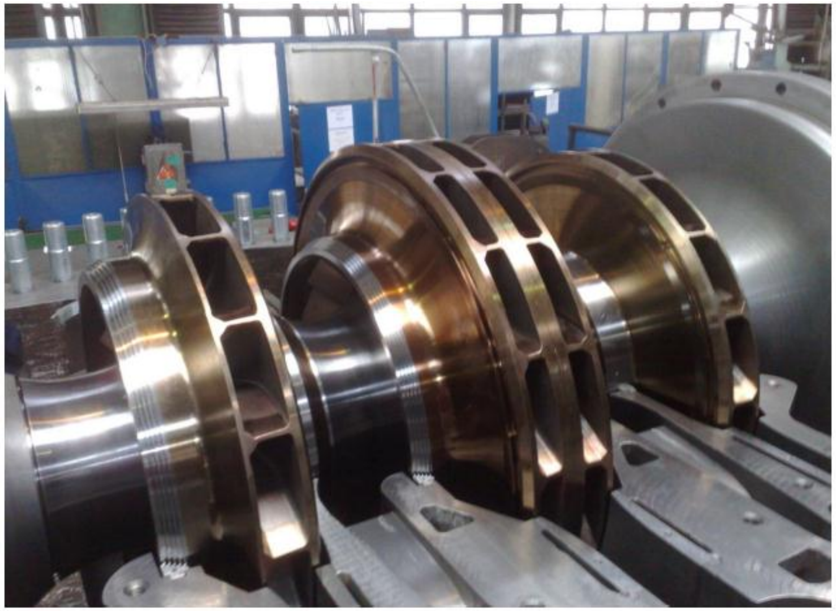
Objectives

- Upgrade the performance of the existing compressor family at Howden ČKD Compressors
- Choice of master stages and a series of derived stages to adapt these to the exact flow conditions required
- Cover a range of flow coefficient ($\phi = \frac{4\dot{V}_0}{\pi U_2 D_2^2}$) between 0.0075 and 0.15
- Preliminary and detailed design of the stages
- Performance testing of selected stages



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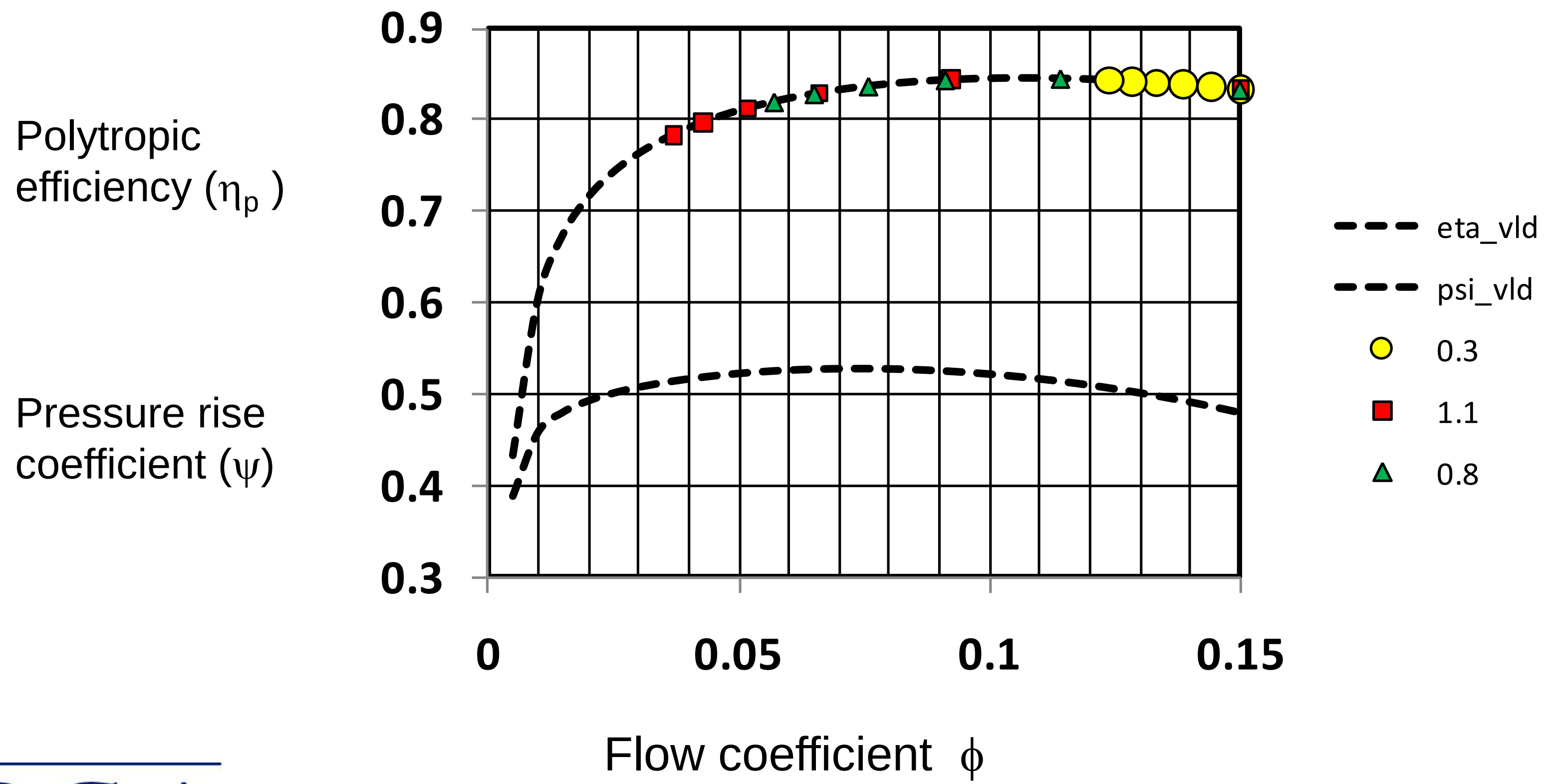
Master and Derived Stages

- For a fixed first stage, the flow coefficient of the downstream stages varies depending on the machine tip speed Mach number ($M_{u_2} = \frac{U_2}{a_{01}}$)

$$\phi_{n+1} = 4\dot{m}/(\rho_{t2}\pi D_2^2 u_2) = (\rho_{t1}/\rho_{t2})\phi_n = \frac{\phi_n}{\left(1+(\gamma-1)\lambda M_{u2}^2\right)^{1/(n-1)}}$$



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Master and Derived Stages

- Col Charles Renard was a designer of airships for the French Army in the 1880’s
- He proposed the system of ‘preferred’ numbers that became ISO 3
- Used it to reduced the number of different balloon ropes kept on inventory from 425 to 17
- It divides a decade into 5, 10, 20 or 40 steps

Col. Charles Renard (1847-1905)

- Step change in flow coefficient was determined by the Renard R40 series
  - 6% ($\sqrt[40]{10}$) change in flow coefficient between successive stages
  - 60 stages to cover the entire range from 0.0075 to 0.15
- Derived stages are trimmed from master stages to achieve intermediate stages

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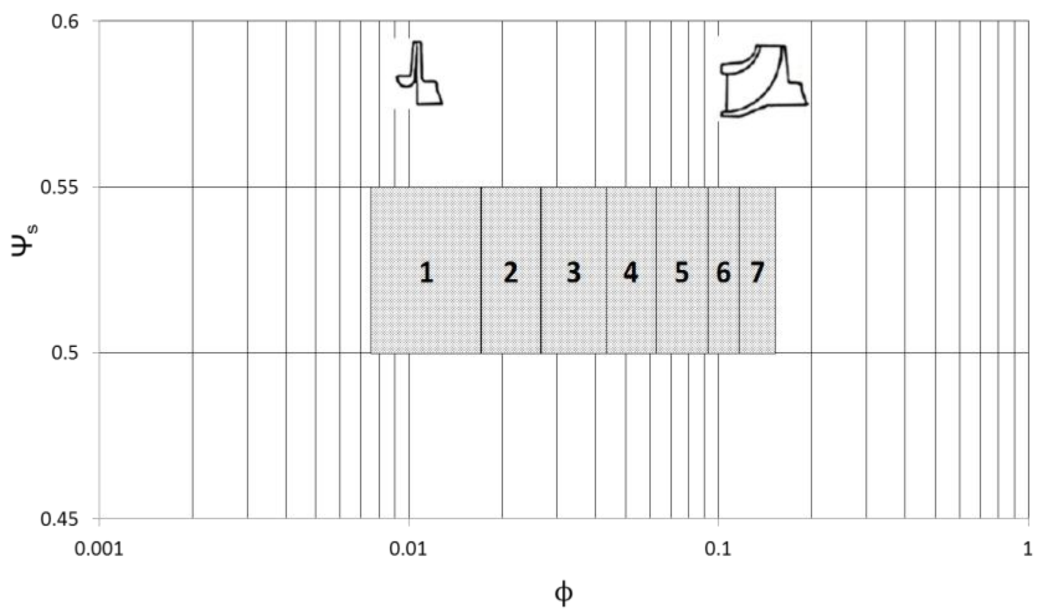
Master and Derived Stages

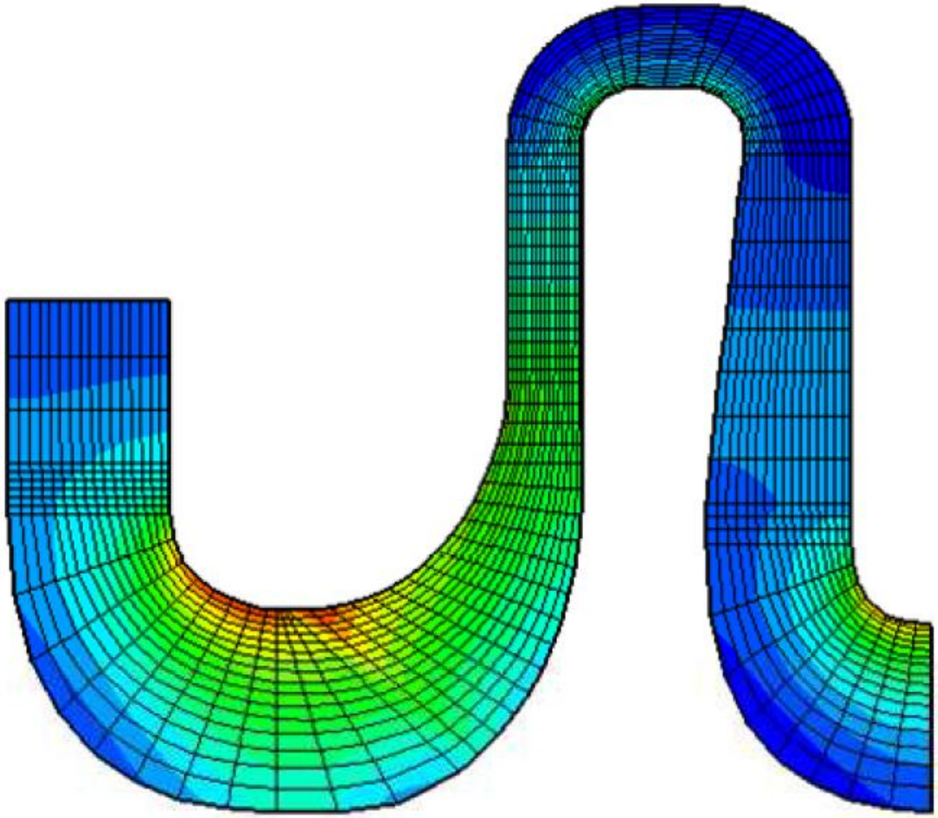
- Designing new stages for each application is not practicable
- Seven master stages were used to cover the required flow range
- The step size can be smaller at high flow coefficients stages and larger at low flow coefficients

  - Rotordynamic advantage in switching earlier to shorter low flow coefficient stages
  - Efficiency drop at high flow coefficients (or more sensitive to trimming)

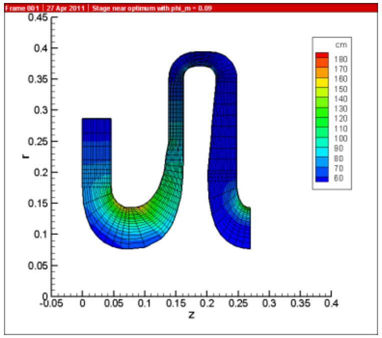


Master and Derived Stages

- Trim profiles were determined from the calculated streamlines in the 2D throughflow calculation of the original master stage to achieve similar
    - Aerodynamic loading
    - Inlet and outlet flow angles
    - Incidence

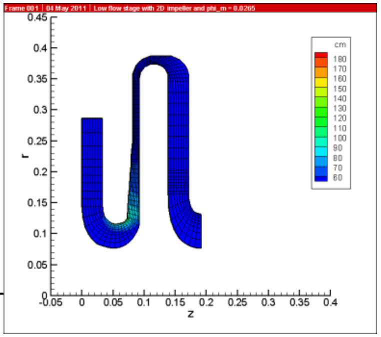


52 Master and Derived Stages



3D stages:

	Master	Derived
$A3$	$\phi_M = 0.1500$	0.1400, 0.1320, 0.1250
$B3$	$\phi_M = 0.1180$	0.1120, 0.1060, 0.1000, 0.0950
$C3$	$\phi_M = 0.0900$	0.0850, 0.8000, 0.0750, 0.0710, 0.0670
$D3$	$\phi_M = 0.0630$	0.0600, 0.0560, 0.0530, 0.0500, 0.0475, 0.0450
~~$E3$~~	~~$\phi_M = 0.0425$~~	~~0.0400, 0.0375, 0.0355, 0.0335, 0.0315, 0.0300, 0.0280~~



2D stages:

	Master	Derived
~~$A2$~~	~~$\phi_M = 0.0630$~~	~~0.0600, 0.0560, 0.0530, 0.0500, 0.0475, 0.0450~~
$B2$	$\phi_M = 0.0425$	0.0400, 0.0375, 0.0355, 0.0335, 0.0315, 0.0300, 0.0280
$C2$	$\phi_M = 0.0265$	0.0250, 0.0236, 0.0224, 0.2120, 0.0200, 0.0190, 0.0180
$D2$	$\phi_M = 0.0170$	0.0160, 0.1500, 0.0140, 0.132, 0.0125, 0.0118, 0.0112
		0.0106, 0.0100, 0.0095, 0.0085, 0.008, 0.0075

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Impeller

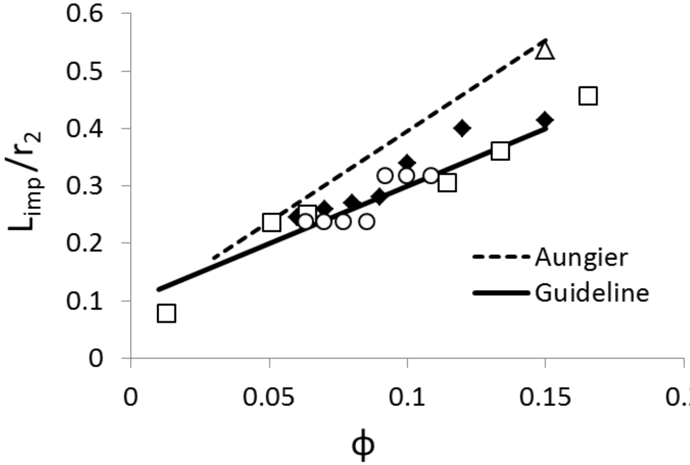
- Impeller **axial length** increases in high flow coefficient stages
- Previous guideline by Aungier

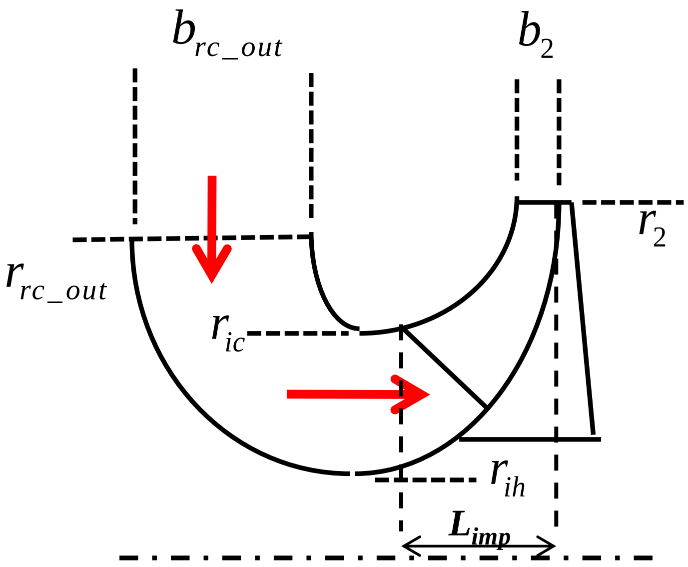
$$\frac{L_{imp}}{r_2} = 0.08 + 3.16\phi$$

- Current guideline results in shorter high flow coefficient stages

$$\frac{L_{imp}}{r_2} = 0.1 + 2\phi$$

- Typically 0.6-0.7 for turbocharger and gas turbine impellers (cf 0.4 from the above equation)





Impeller

- Impeller **eye radius ratio**

$$\frac{r_{ic}}{r_2} = 0.5 + 1.5\phi$$

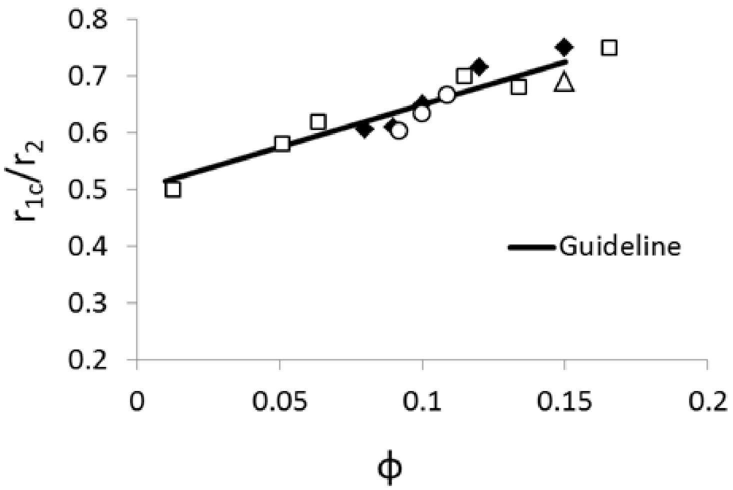
- Impeller **hub radius ratio**

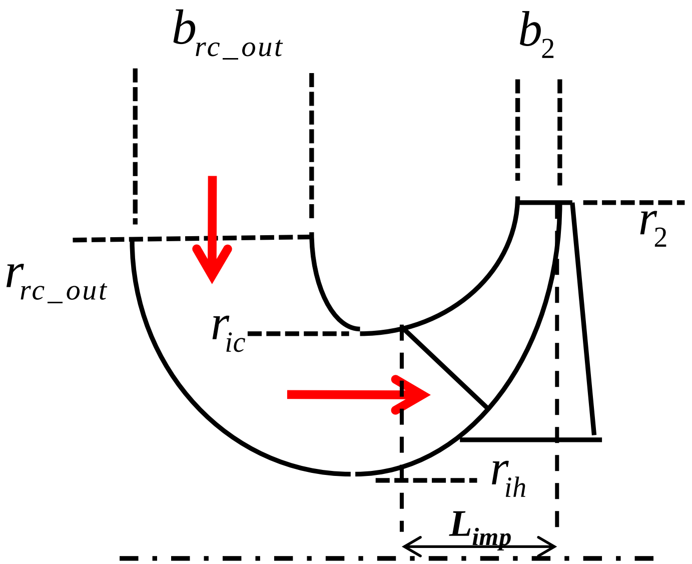
$$\frac{r_{ih}}{r_2} = 0.35$$

- Impeller **outlet width ratio**

$$\frac{b_2}{r_2} = 0.05 + 0.8\phi$$

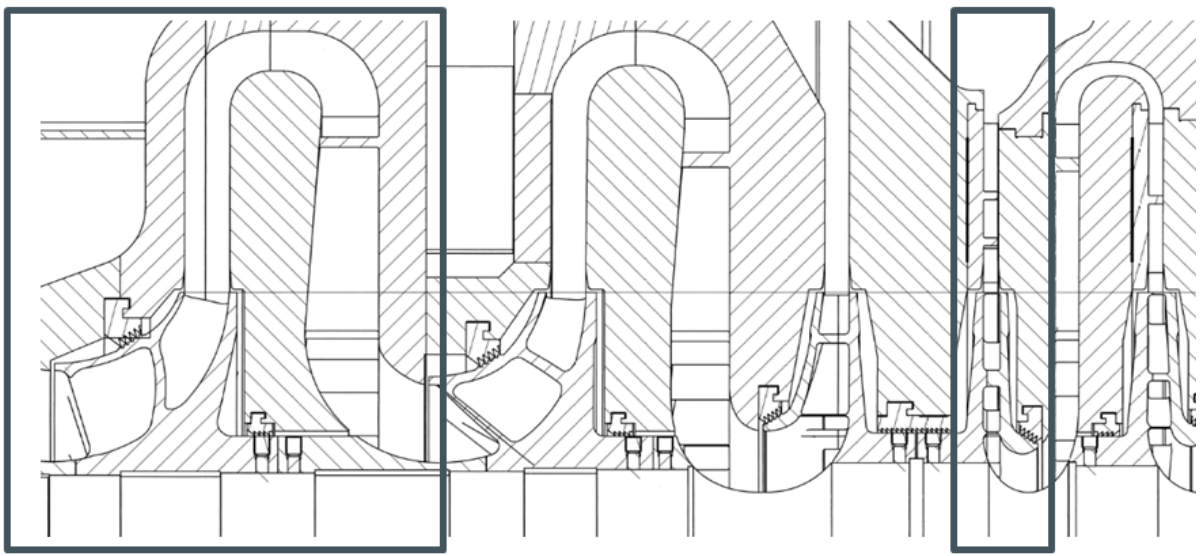
- 10-20% pinch in the diffuser, determined in the detailed design





Diffuser

- Diffuser radius ratio of 1.6 to reduce the kinetic energy at inlet to the crossover bend
- Vaneless diffusers at high and medium flow coefficients
  - Wider operating range



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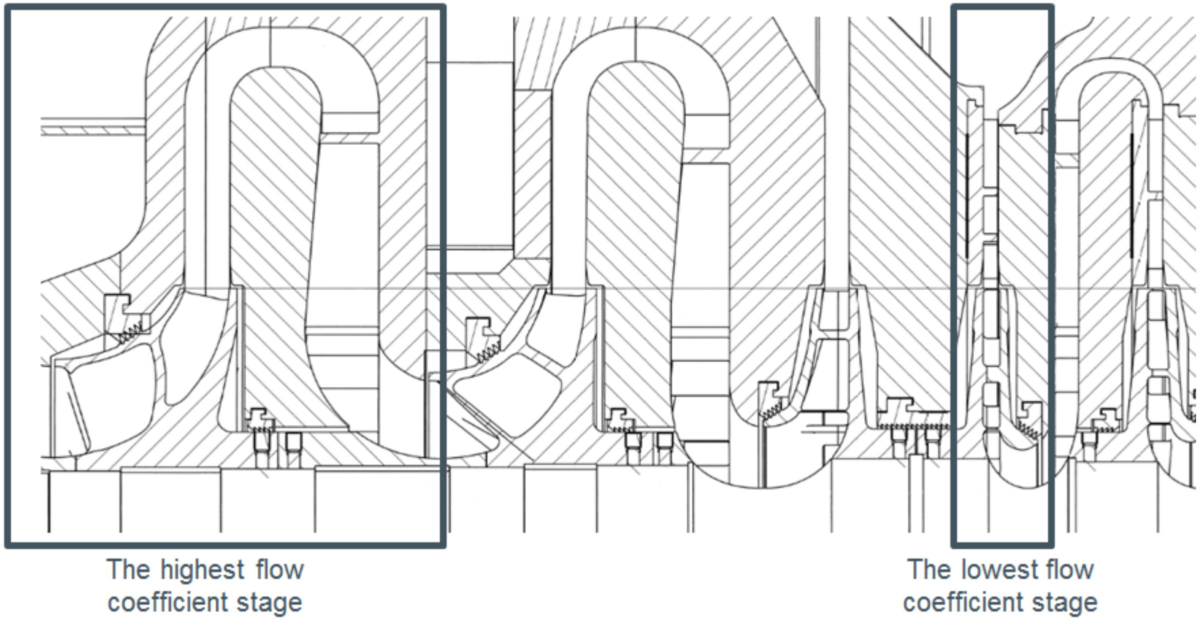
Diffuser

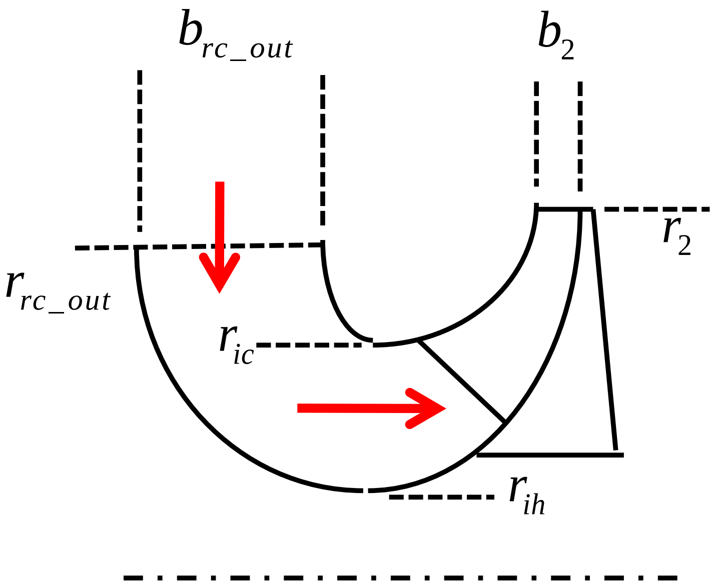
- Vaned diffuser at low flow coefficient stages:
  - High loss generation in excessively narrow diffuser passages
  - larger impeller tip widths have been used to widen the passage
  - Vaned diffusers have been used to avoid possible flow instabilities and high losses associated with high flow angles in vaneless diffusers



Return Channel

- Accelerating flow from deswirl outlet to the inlet of the downstream impeller to avoid possible flow separations
- $\boldsymbol{b_{rc\_out}}$ depends on the flow coefficient of the downstream impeller (ϕ_{n+1})
- ϕ_{n+1} depends on the density ratio and hence on the tip speed Mach number (M_{u2}) of the upstream stage

$$\phi_{n+1} = 4\dot{m}/(\rho_{t2}\pi D_2^2 u_2) = (\rho_{t1}/\rho_{t2})\phi_n = \frac{\phi_n}{\left(1+(\gamma-1)\lambda M_{u2}^2\right)^{1/(n-1)}}$$



- A return channel designed for high M_{u2} results in excessive deceleration at low speed
- Return channel width is typically larger than the diffuser width

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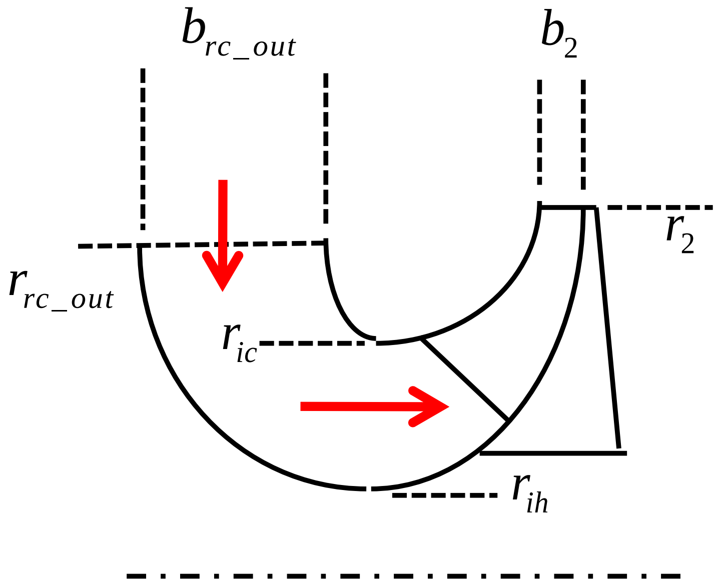
Return Channel

- From the guidelines presented before it can be shown:

$$b_{rc\_out}/r_2 = \left(\frac{A_o}{A_i}\right)\left(\frac{r_2}{Rr_{ic}}\right)\left(\frac{\left[(r_{ic}/r_2)^2 - (r_{ih}/r_2)^2\right]}{2}\right)$$

- $R = \frac{r_{rc\_out}}{r_{ic}} = 1.25 - 1.35$
  - Smooth bend at the inlet
- A_0/A_i =1.25 to 1.35
  - 25% to 35% acceleration upstream of the impeller



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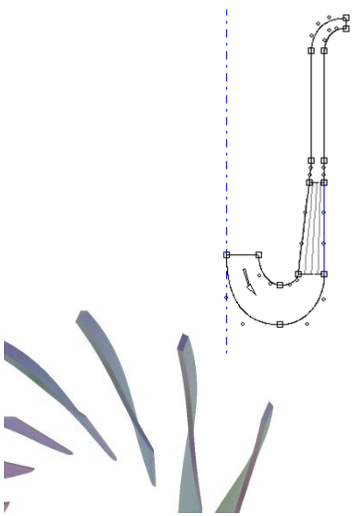
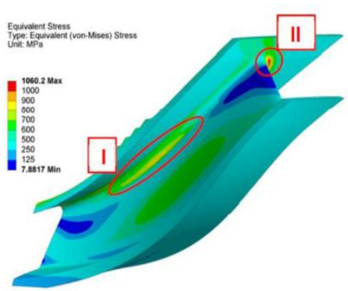
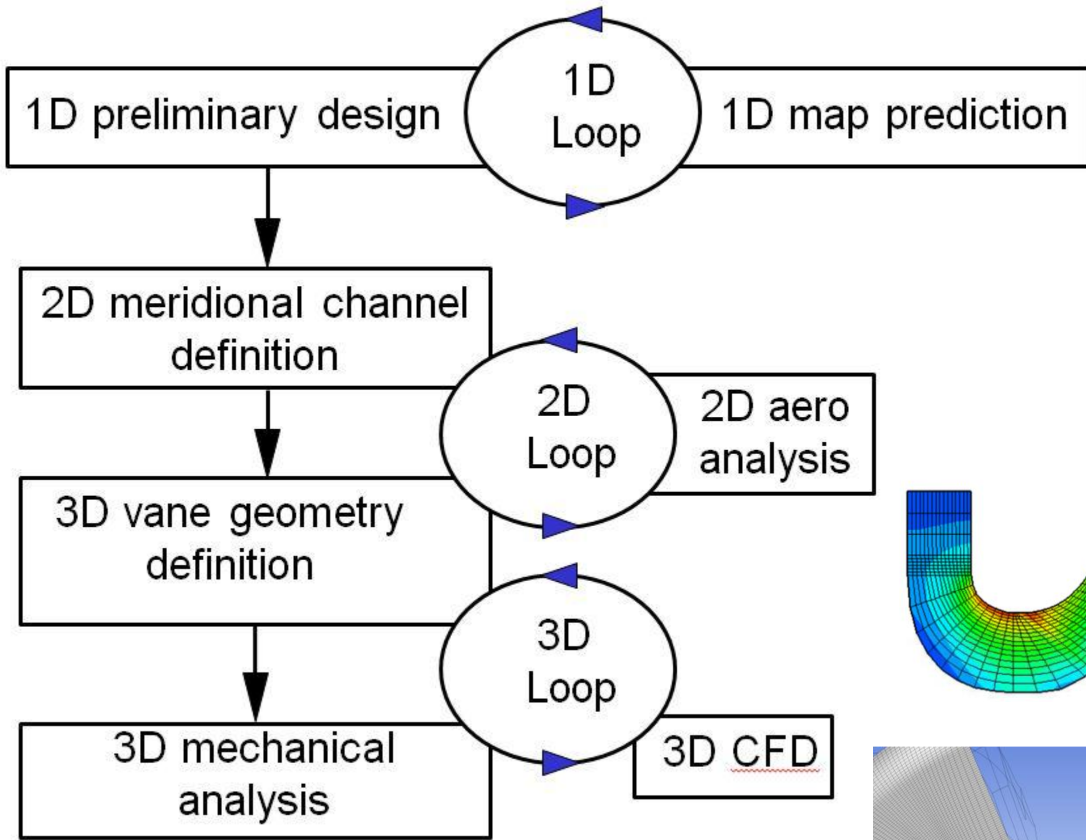
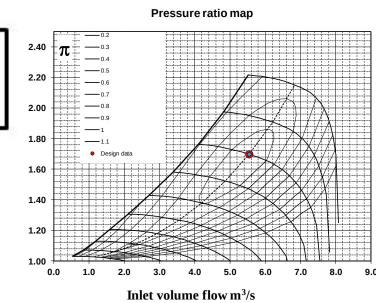
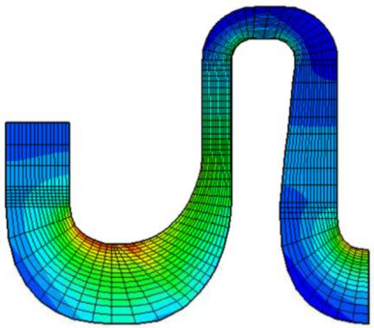
Design process

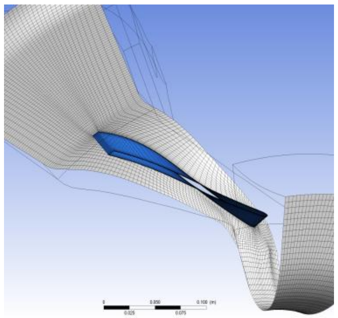






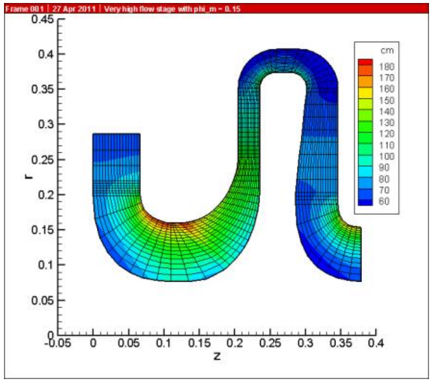


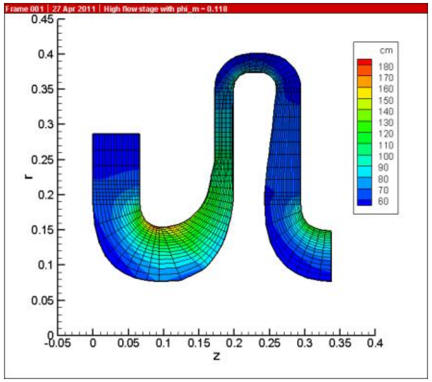


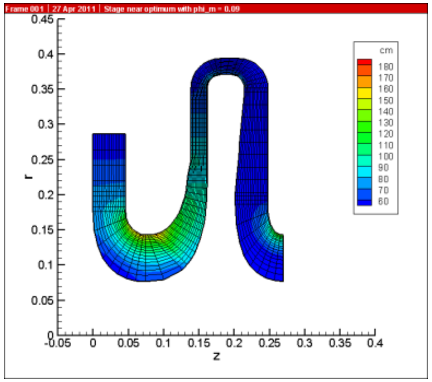


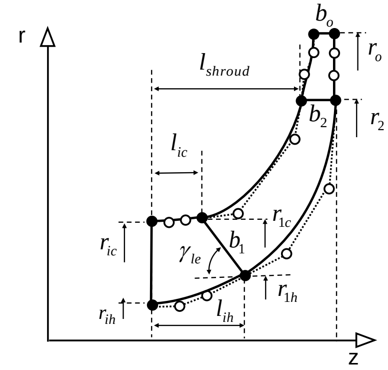
Parameterised geometry generation of flow channel

- 3D stages at high ϕ

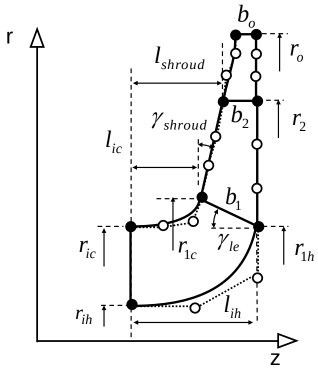


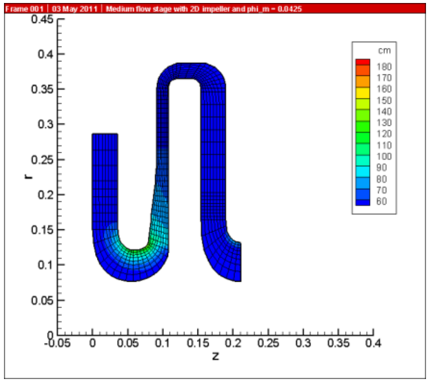


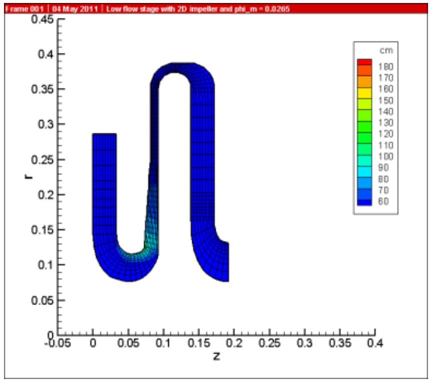


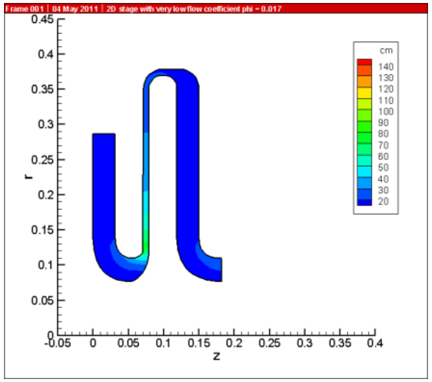


- 2D stages at lower ϕ









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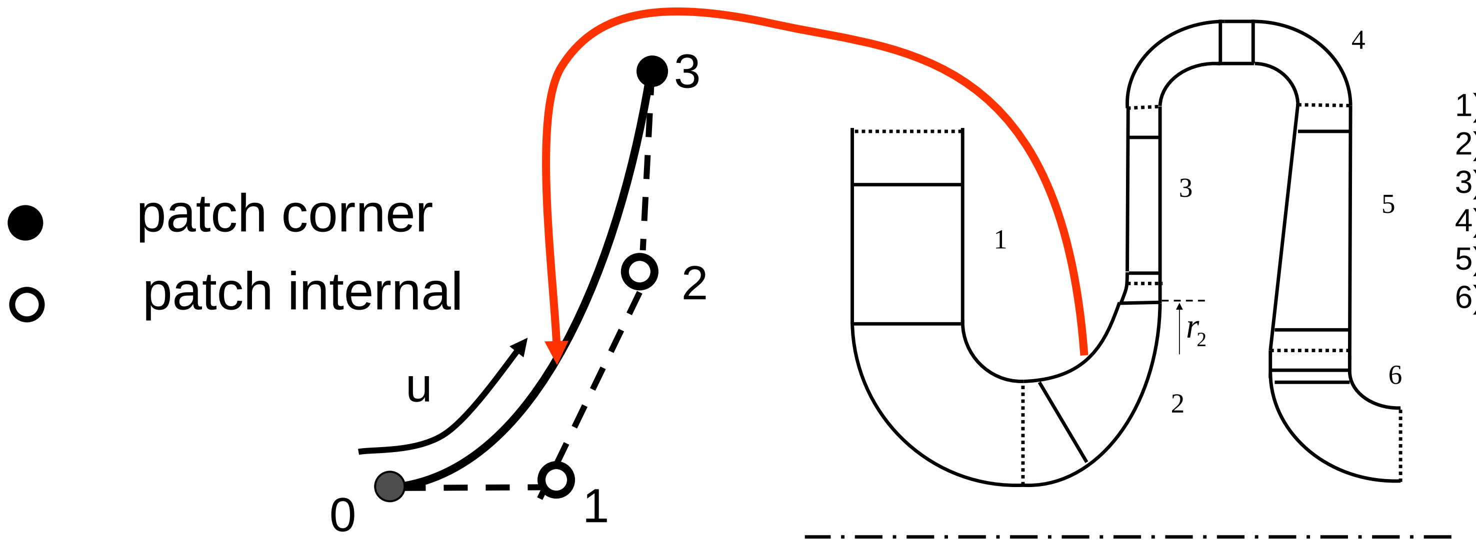
Parameterised geometry generation of flow channel

- Flow channel of full stage modelled with Bezier curves set up as patches

$$\vec{R} = (1-u)^3 \vec{P}_0 + 3u(1-u)^2 \vec{P}_1 + 3u^2(1-u)\vec{P}_2 + u^3 \vec{P}_3$$



1) Inlet bend
2) Impeller
3) Diffuser
4) Crossover bend
5) Return channel
6) Outlet

- Vista GEO
  - Based on method of Casey (1983)
  - Similar system system as used in ANSYS Bladegen
  - Links to throughflow, mechanical analysis and to ANSYS bladegen

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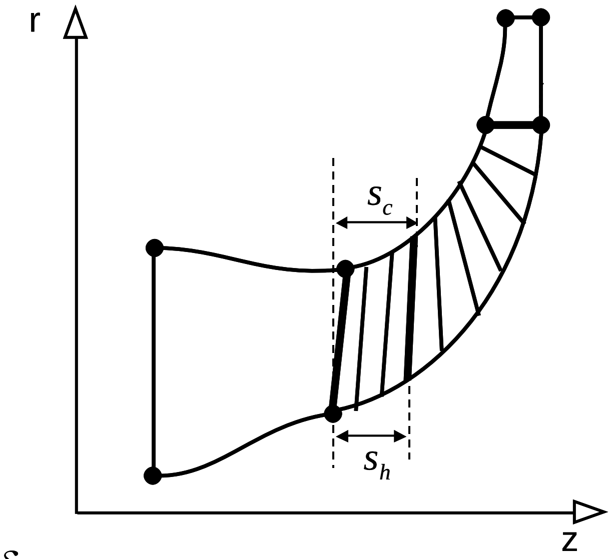
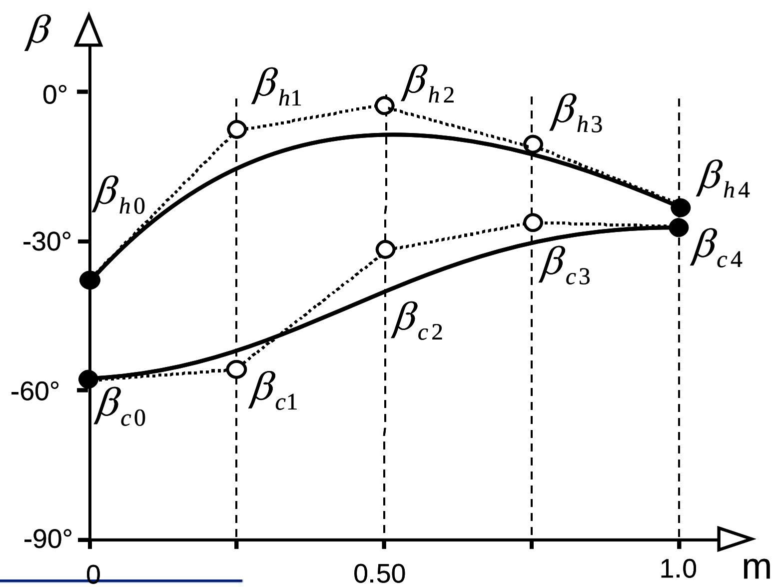
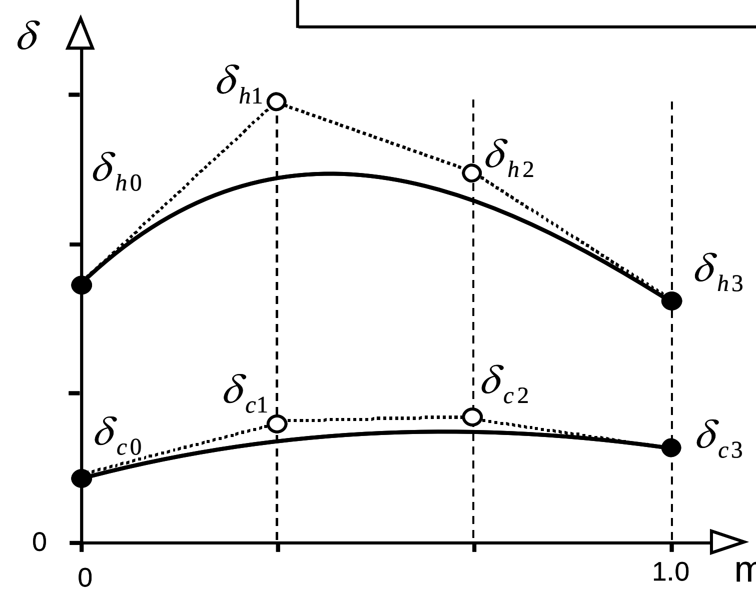
Geometry generation of blades

- Blades modelled with 24 free parameters, amenable to automated optimisation
    - Ruled surface defined by hub and casing blade angles and thickness distributions
    - Splitter leading edge position
    - Ellipse parameters for rounding of edges







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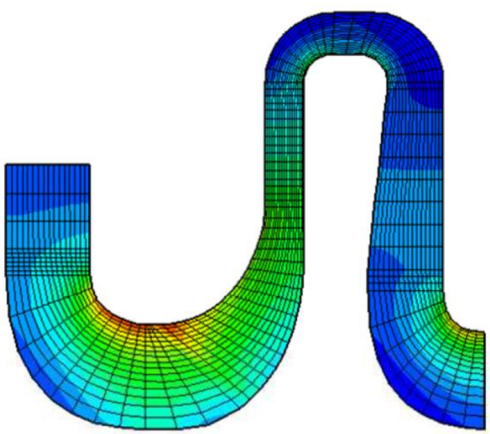
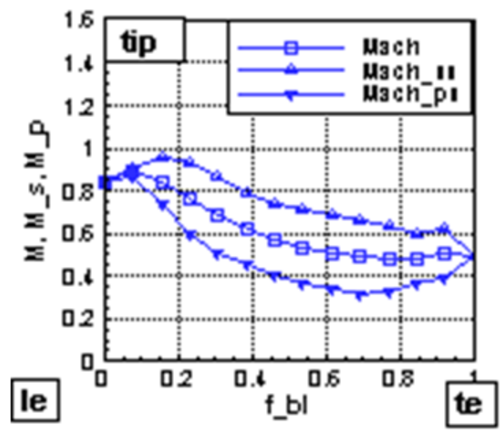
Throughflow calculations (Vista TF)

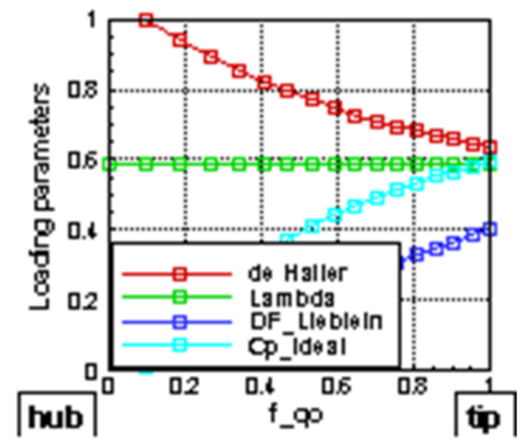
- Streamline curvature solution on a mean S2 surface
- Stanitz and Prian (1952) approximation for the blade to blade variation:

$$\frac{W_s - W_p}{r\Delta\vartheta} = 2\Omega\frac{\partial r}{\partial m}\cos\beta + W\cos^2\beta\frac{\partial\beta}{\partial m} + \frac{\sin^2\beta\cos\beta}{r}\frac{\partial}{\partial m}(rW)$$

- Experience-calibrated loading parameters:

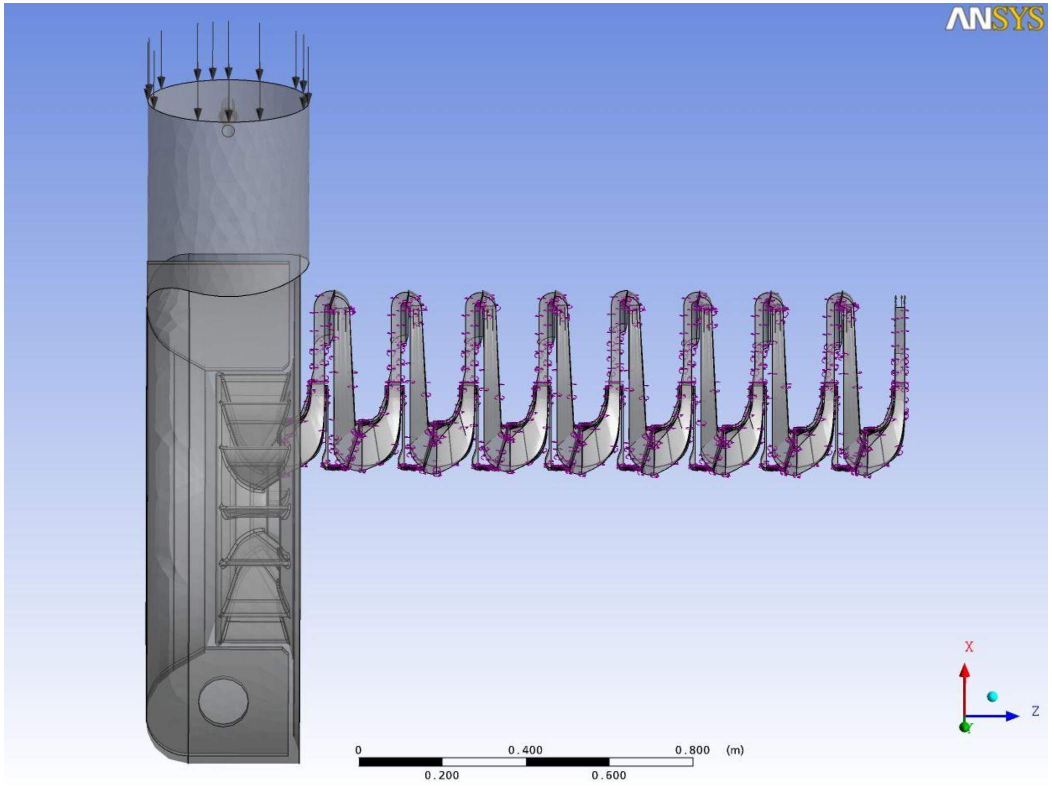


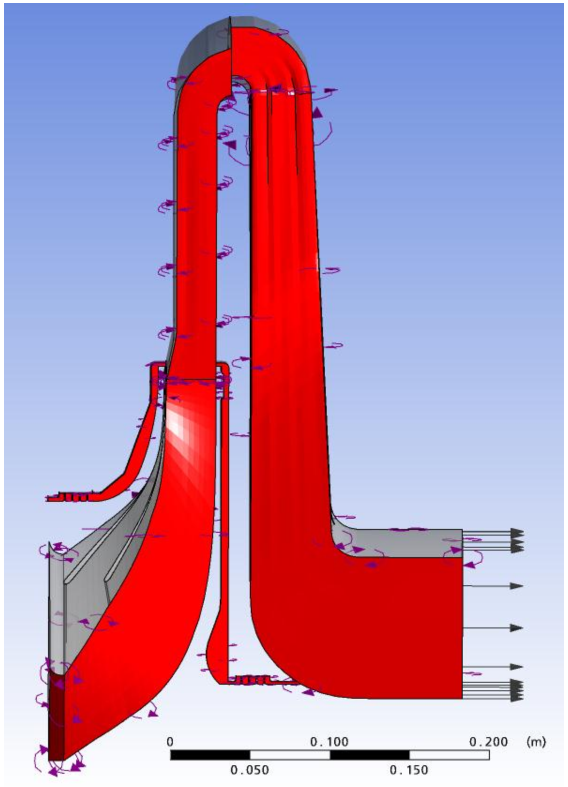




CFD analysis (ANSYS CFX)

- 9-stage, real gas calculation (extent of our experience)





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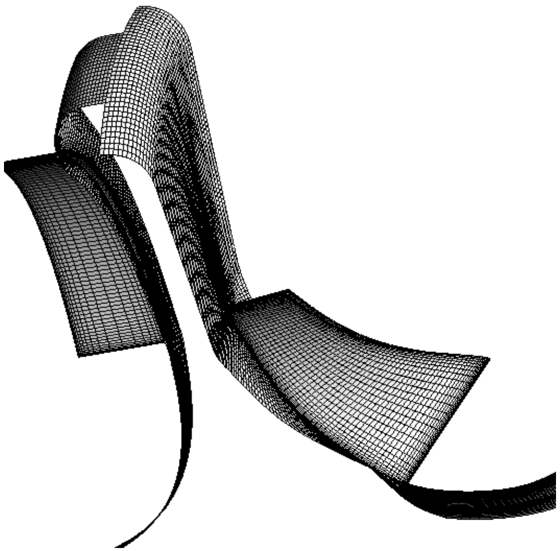
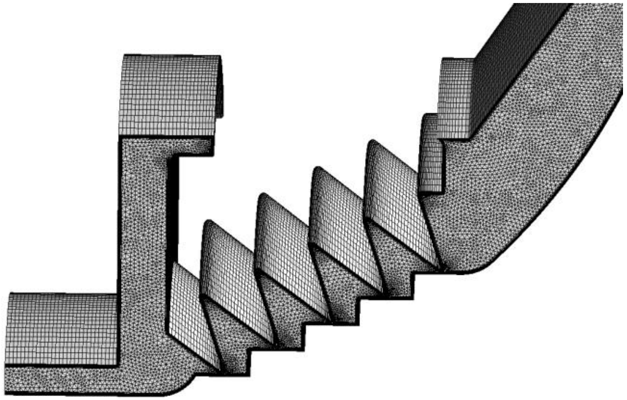
CFD analysis (ANSYS CFX)

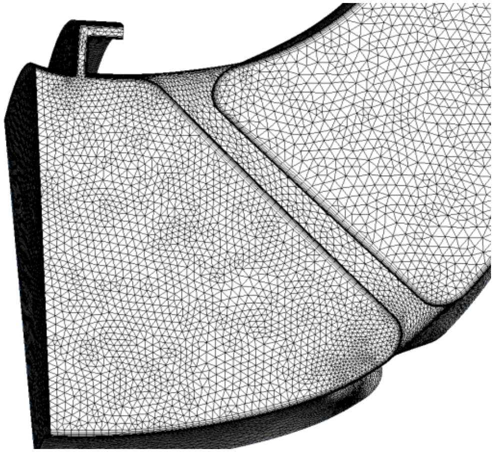
- Detailed optimisation is based on 3D CFD calculations:
  - Single passage steady state calculations
  - Structured grid in bladed passages using ANSYS Turbogrid (ATM)
  - Effect of fillets and leakages can be ignored in the initial design loop
  - Unstructured mesh for complex parts (larger mesh size)



Gas path only



Shroud leakage path



Impeller with fillets

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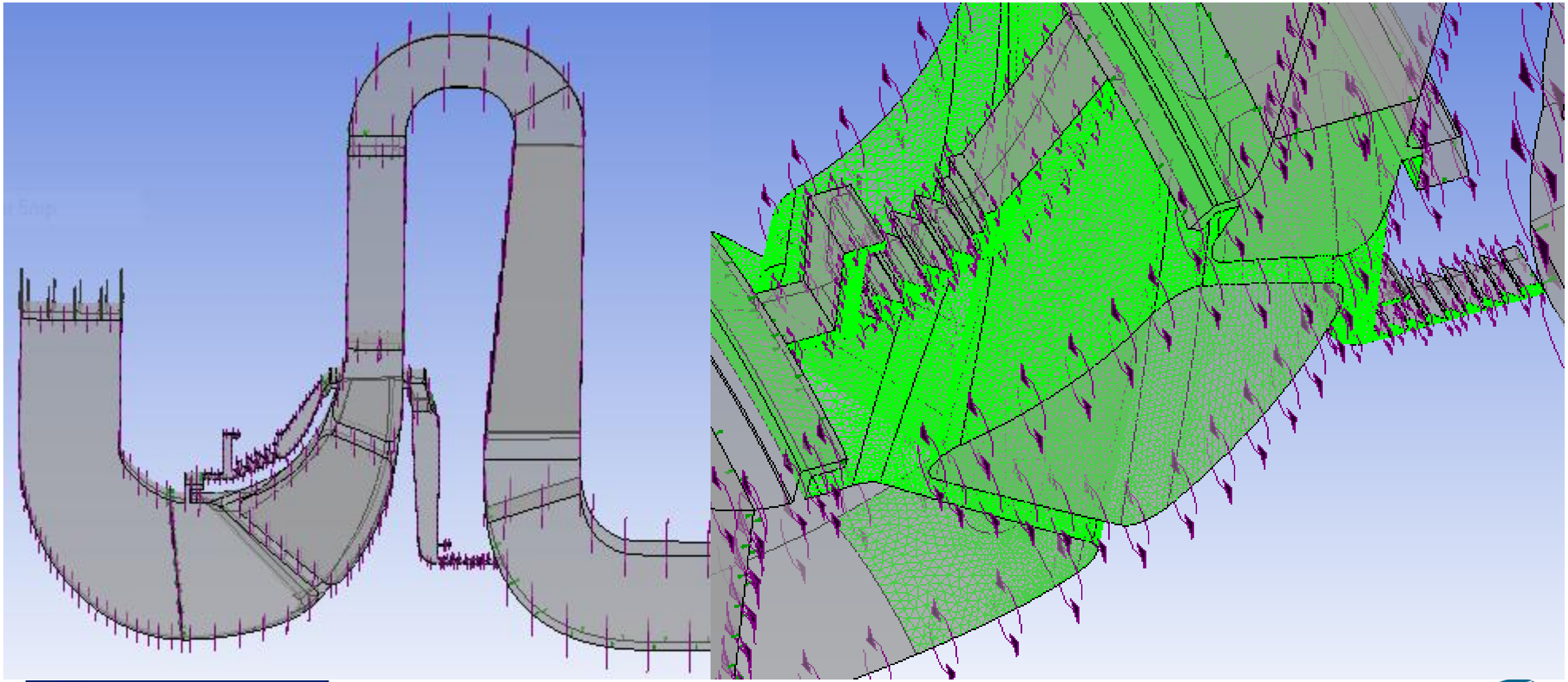
CFD analysis (ANSYS CFX)

- Calculations using CFX 17.1 with SST turbulence model
- Mesh size typically 4m nodes (3.5m in impeller, diffuser and leakage paths)
- Compared to typically 250k nodes for a ‘design’ iteration (using k-ε)



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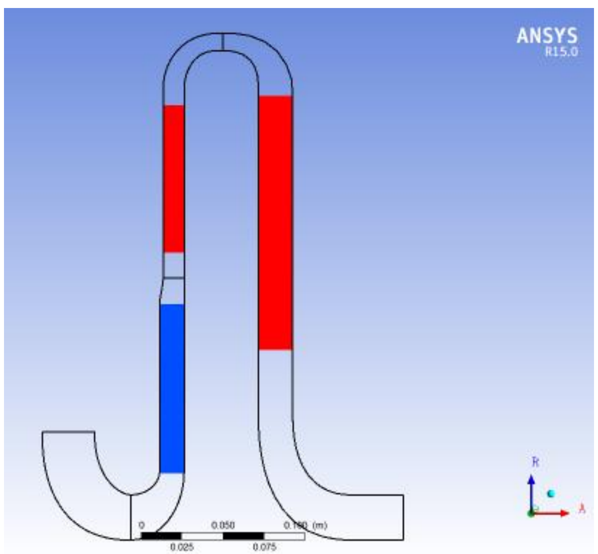
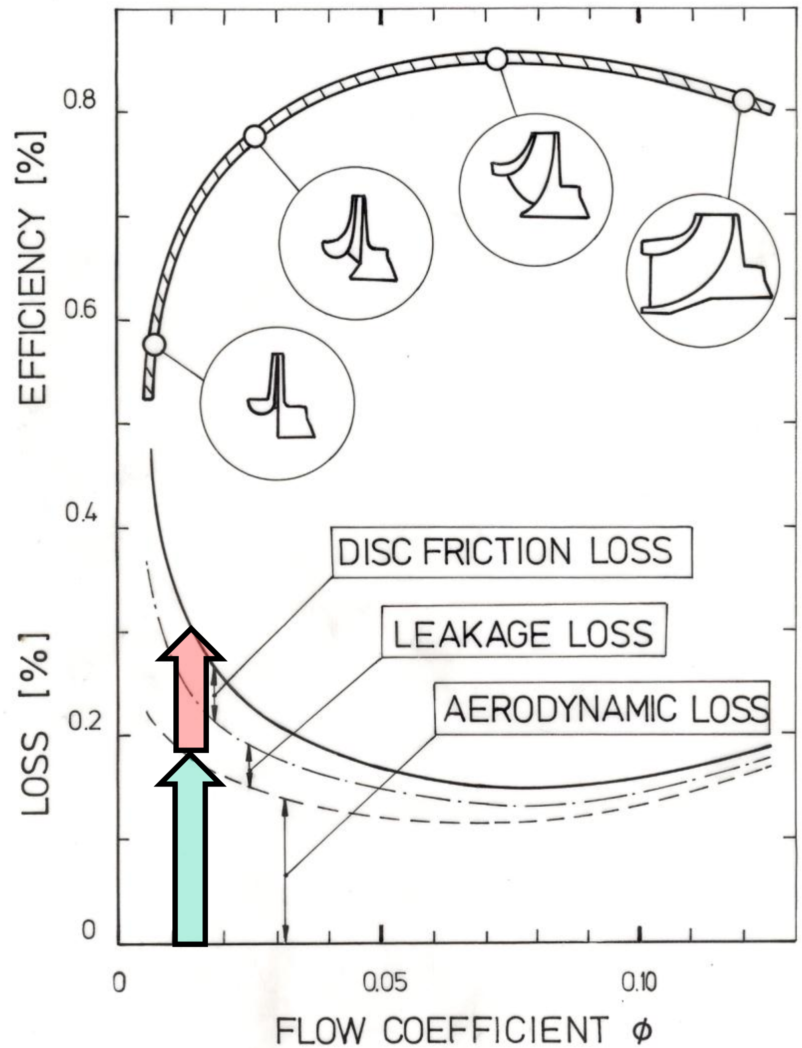
Efficiency as a function of flow coefft.

3D Stages	
Stage	ϕ_M
A3	0.150
B3	0.118
C3	0.090
D3	0.063
E3	0.0425

2D Stages	
Stage	ϕ_M
$\Phi_M =$	$4V/\pi UD^2$
A2	0.063
B2	0.0425
C2	0.0265
D2	0.017





$\phi = V/UD^2$

Commercial-in-Confidence

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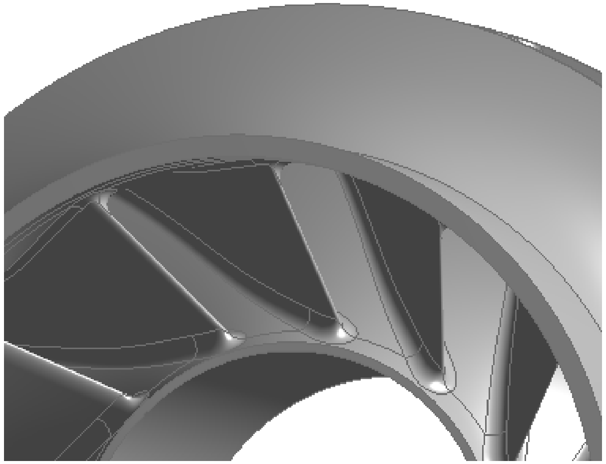
Impeller Vanes

- All shrouded impellers
- 2D vanes for the lower flow range ($\phi \leq 0.046$)
  - Brazed impellers
  - Brazing plane decided based on stress analysis
- 3D vanes for the high and medium flow range
  - Single-piece milled impellers
- operating tip-speeds up to 380 m/s (X5CrNi) were tested
- 500 m/s is possible with the use of titanium alloys



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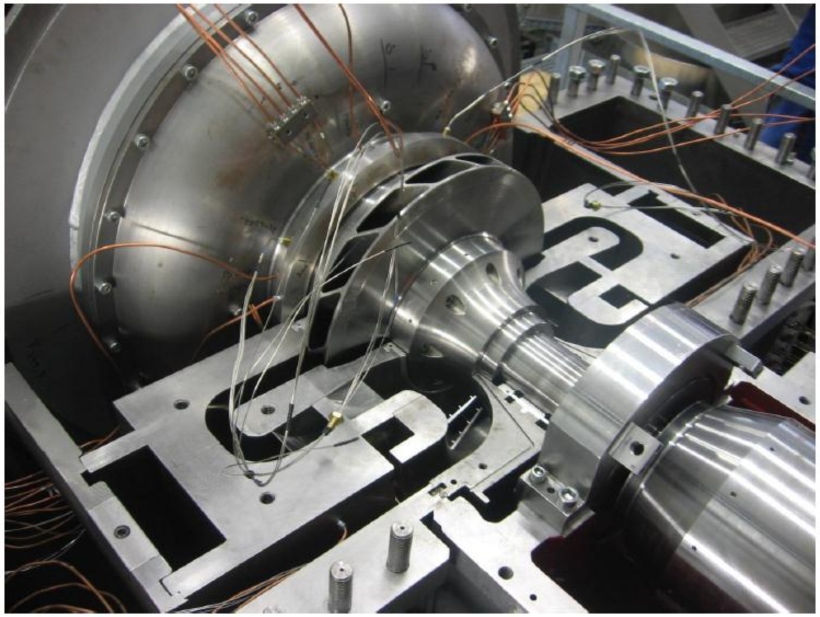
Performance Testing

- Newly built, dedicated test facility at Howden ČKD Compressors (DARINA)
- The master stages were tested along with their smallest trim or derived stages at a range of tip speed Mach number from 0.3 to 1.1
- Detailed flow measurements were taken at five planes at impeller inlet, impeller outlet, diffuser outlet, return-channel inlet and return-channel outlet
- More than 120 pressure and 50 temperature probes were used
- Kiel probes, 3-hole probes and high frequency pressure transducers



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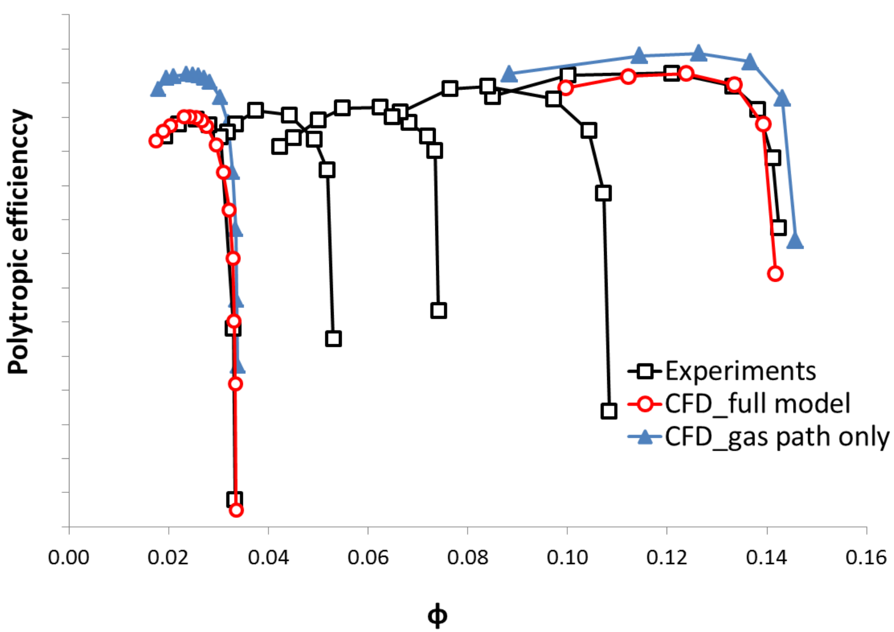
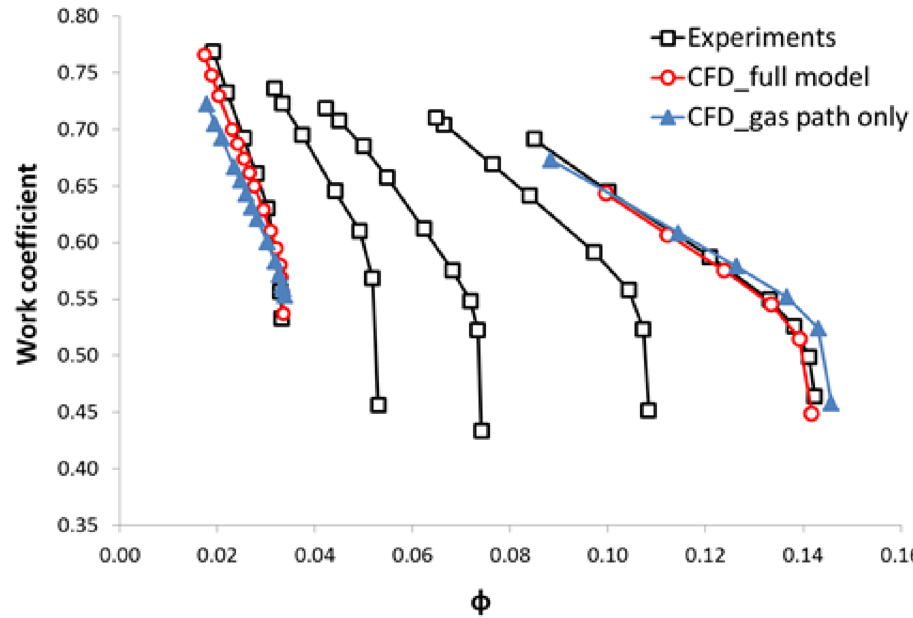
CFD analysis (ANSYS CFX)

- Fillets and leakages need to be included for accurate prediction of performance
- Large effects of the leakage flow on efficiency at low flow coefficients





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Howden

Outline

- Objectives
- Master and Derived Stages
- 1D Design Guidelines
- Detailed design
- Manufacture and Testing
- Summary

Summary

- The design of a new family of process compressor stages using modern design methods has been described.
- The guidelines for preliminary design of the stages has been presented and aspects of the detailed design discussed.
- The test results show that the performance objectives have been achieved and the design tools have been effective
- Comparison of the CFD and test results confirm that the inclusion of real geometry features is necessary to obtain good agreement with the measured performance