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# Free-Form Versus Ruled Inducer Design in a Transonic Centrifugal Impeller

**H. Hazby** **C. Robinson** **M. Casey**
PCA Engineers Ltd., UK

**D. Rusch** **R. Hunziker**
ABB Turbo Systems Ltd., Switzerland

# Outline of this talk

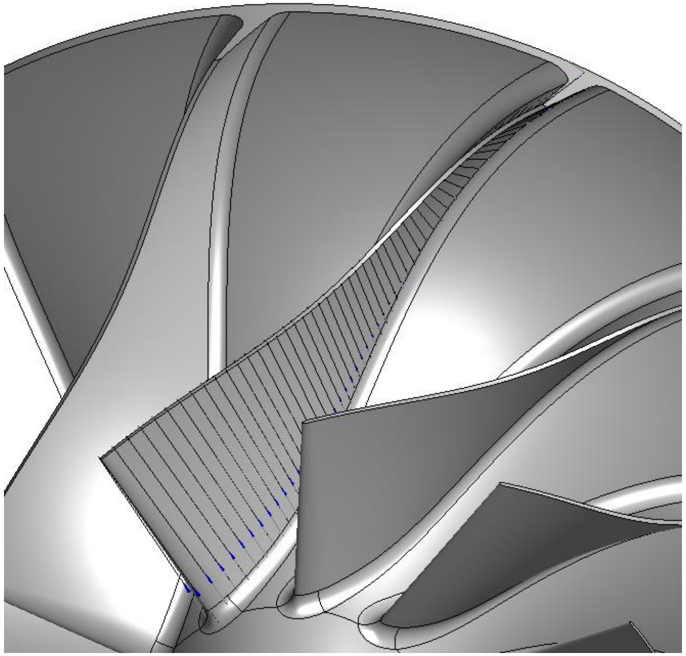
- Background and objectives
- Numerical procedure
- Impeller designs
    - Datum impeller
    - Free-form impellers
- Test results
- Part speed operation
- Conclusions

# Ruled impeller design

- Commonly used to allow manufacturing by **Flank Milling**
- Surfaces are defined using ‘straight lines’ or ‘ruled elements’
- Angle, thickness and lean distributions are specified only on hub and shroud surfaces

✓ Lower manufacturing and design costs

✗ Less control over the geometry in the inner part of the blade



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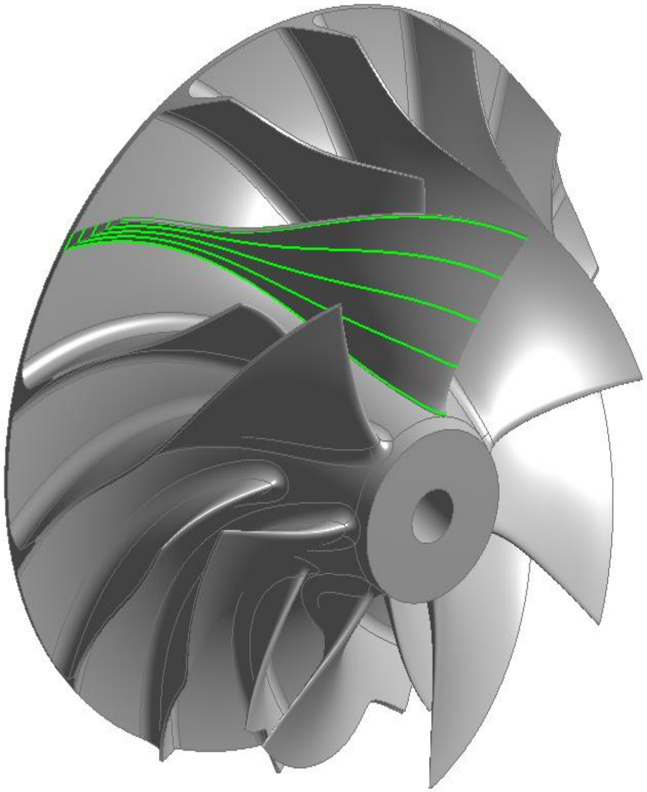
# Free-form impeller design

- Removes the geometrical constraints from the inner part of the blade
- Non-linear angle, thickness and lean distributions can be specified at several span-wise sections
- Needs to be manufactured by **Point Milling**

✗ Higher manufacturing and design costs

✓ Control over the geometry in inner part of the blade



# Free-form vs ruled impeller

- In high speed applications, where shock losses are significant, careful control of the geometry in the inner part of the blade can be beneficial
- Lack of back-to-back studies to determine the performance benefits of free-form impeller designs
- The **objective** of the current work was to carry out a systematic comparison between ruled and free-form designs for a transonic compressor
- Designed by the same individual to ensure consistent  design philosophy

**Hazby et al (2014)**

**Elfert et. at (2016)**

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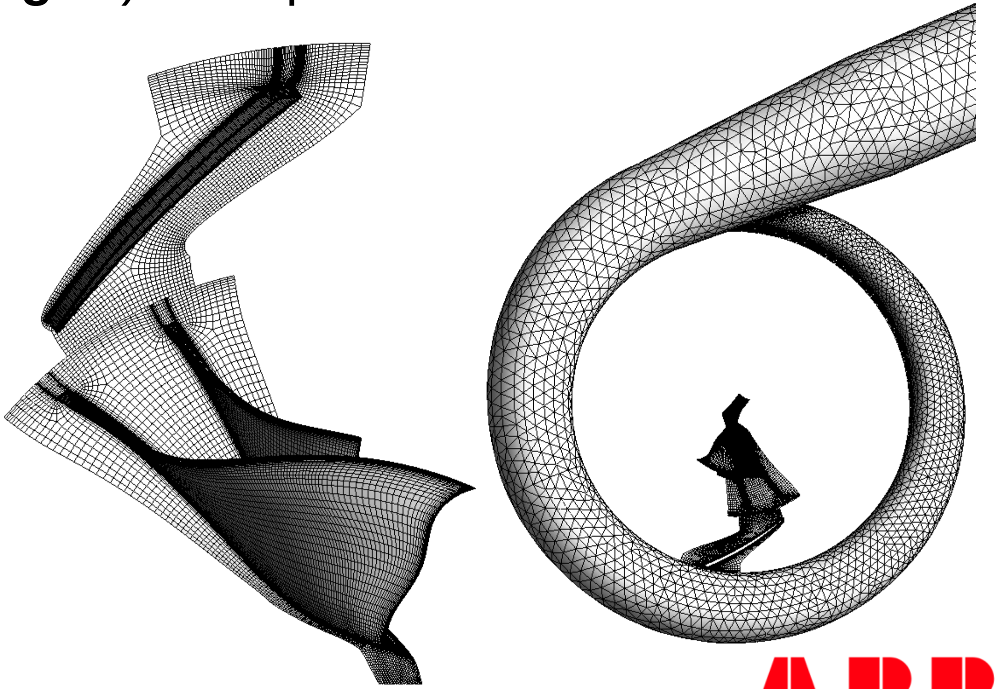
# Numerical procedure

- Impeller blades were designed **in ANSYS Bladegen** and checked for mechanical integrity using **ANSYS Mechanical**
- **ANSYS CFX** was used for single passage steady state calculations
- Structured mesh (**ANSYS Turbogrid**) for impeller and diffuser with 500k and 200k nodes, respectively
- Unstructured mesh with 500k nodes and 10 prism layers inside the volute
- **k-ε Turbulence model** with scalable wall functions



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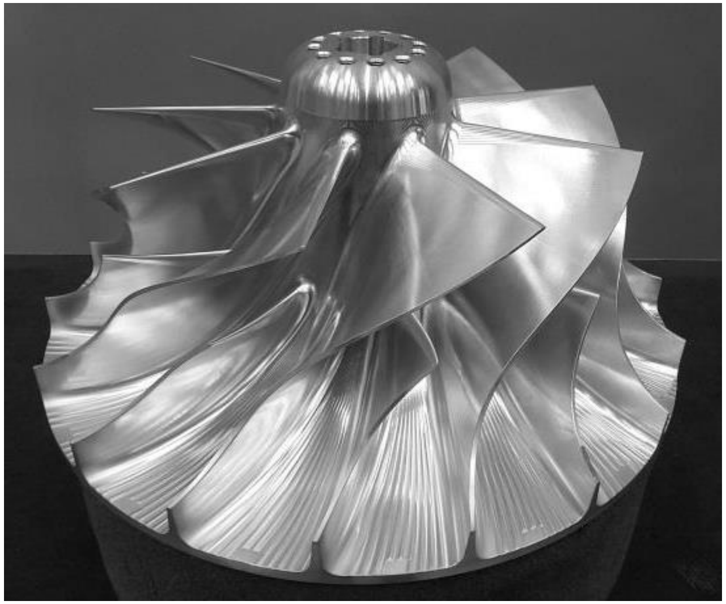
# Datum impeller

- **Ruled design**, using straight line generators
- A high pressure ratio impeller for Marine Turbocharger applications
- Inducer tip relative Mach number of 1.4 at the design point
- Vaned diffuser
- High efficiency levels, representative of the state-of-the-art performance
- Suitable to be used as a datum



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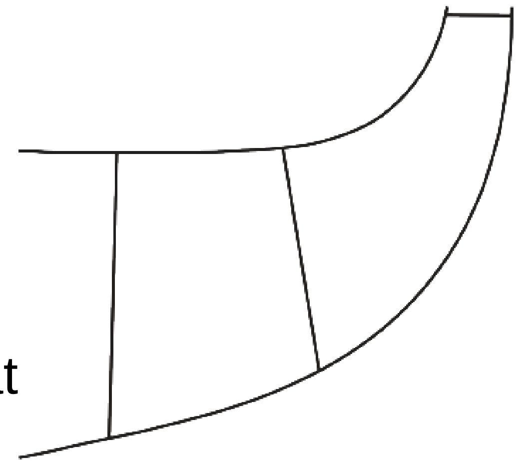
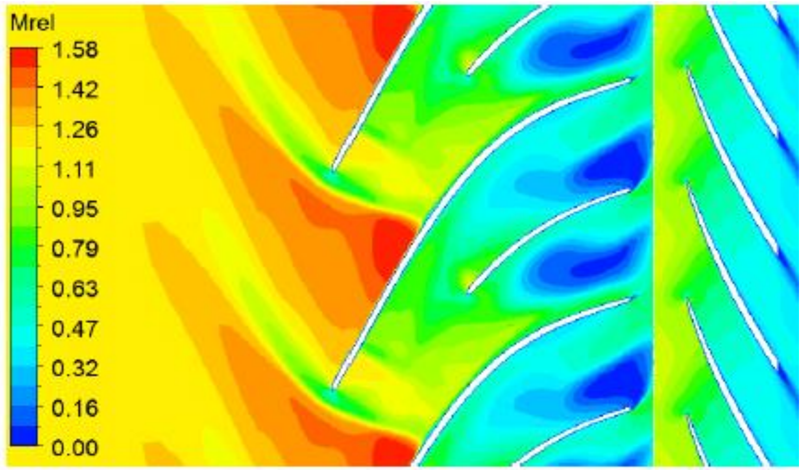
# Datum impeller

- 9+9 vanes and 17° backsweep angle
- LE is swept backward for mechanical reasons
- Independent splitter design
- Low curvature in the uncovered part of the passage at the tip



- The tip section is not fully started at the design condition with a bow shock standing upstream of the main blade leading edge




**Contours of relative Mach number at 90% span**

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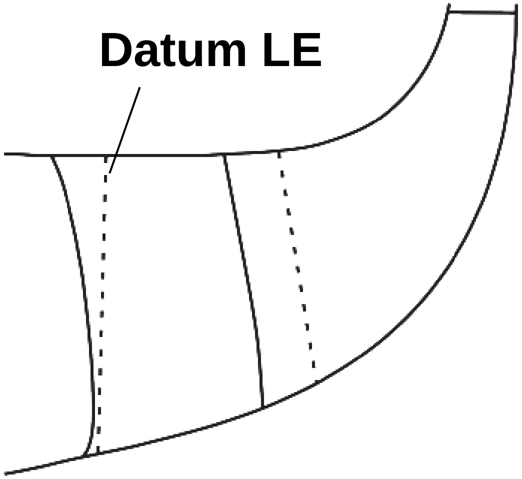
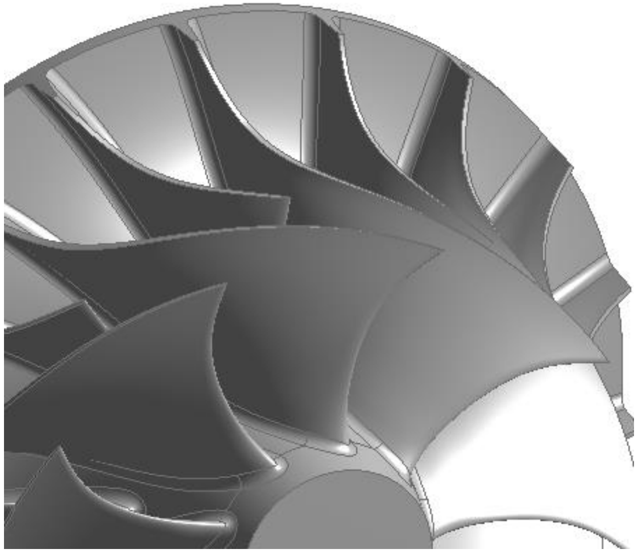
# Forward swept impeller

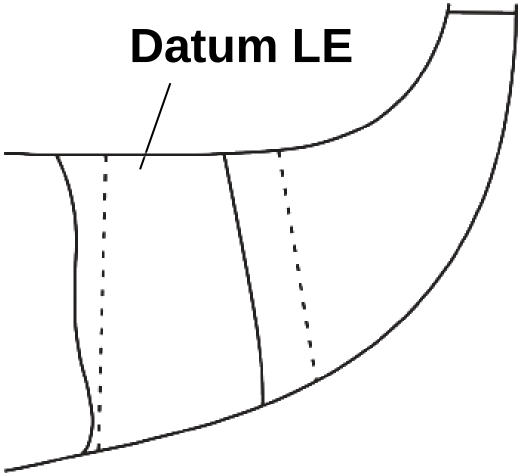
- Forward LE sweep in the upper span
- Increased meridional chord at the tip
- Similar design at TE (slightly higher work)
- Forward sweep of the LE generally:
    - Moves the shock further downstream and reduces the loading at the tip
    - Reduces 1F frequency. It may need thicker blade profiles at lower part

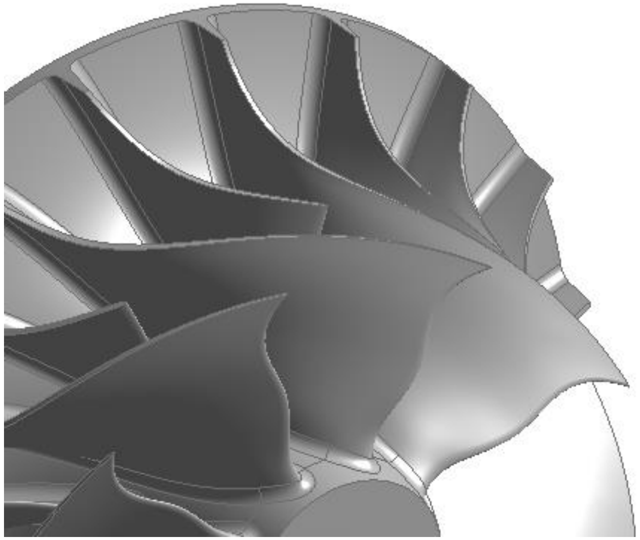


# Barreled forward swept impeller

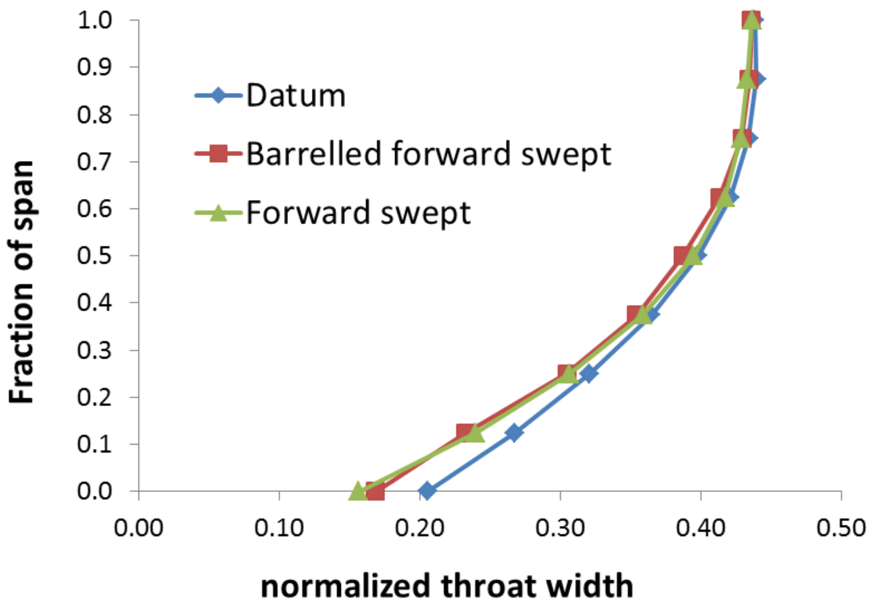
- Blade profiles at hub and shroud are the same as the forward swept impeller
- Increased meridional chord at 50% of the span
- 12% higher 1F frequency compare to the Forward swept impeller

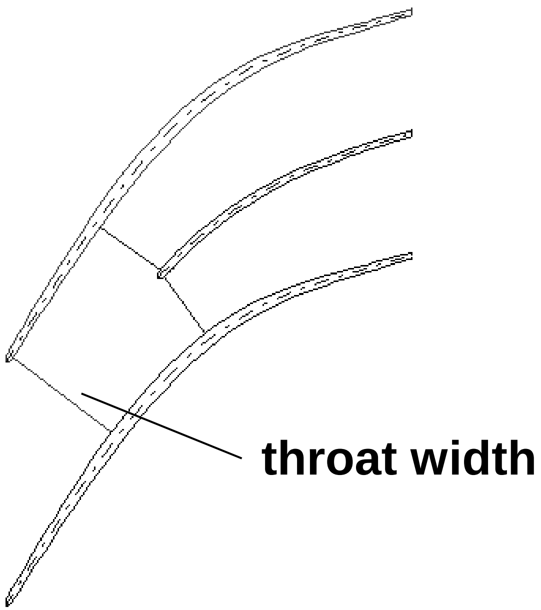


# Throat width distribution

- All three blades have similar throat width distribution in the upper part of the span
- Swept impellers have smaller throat area near the hub

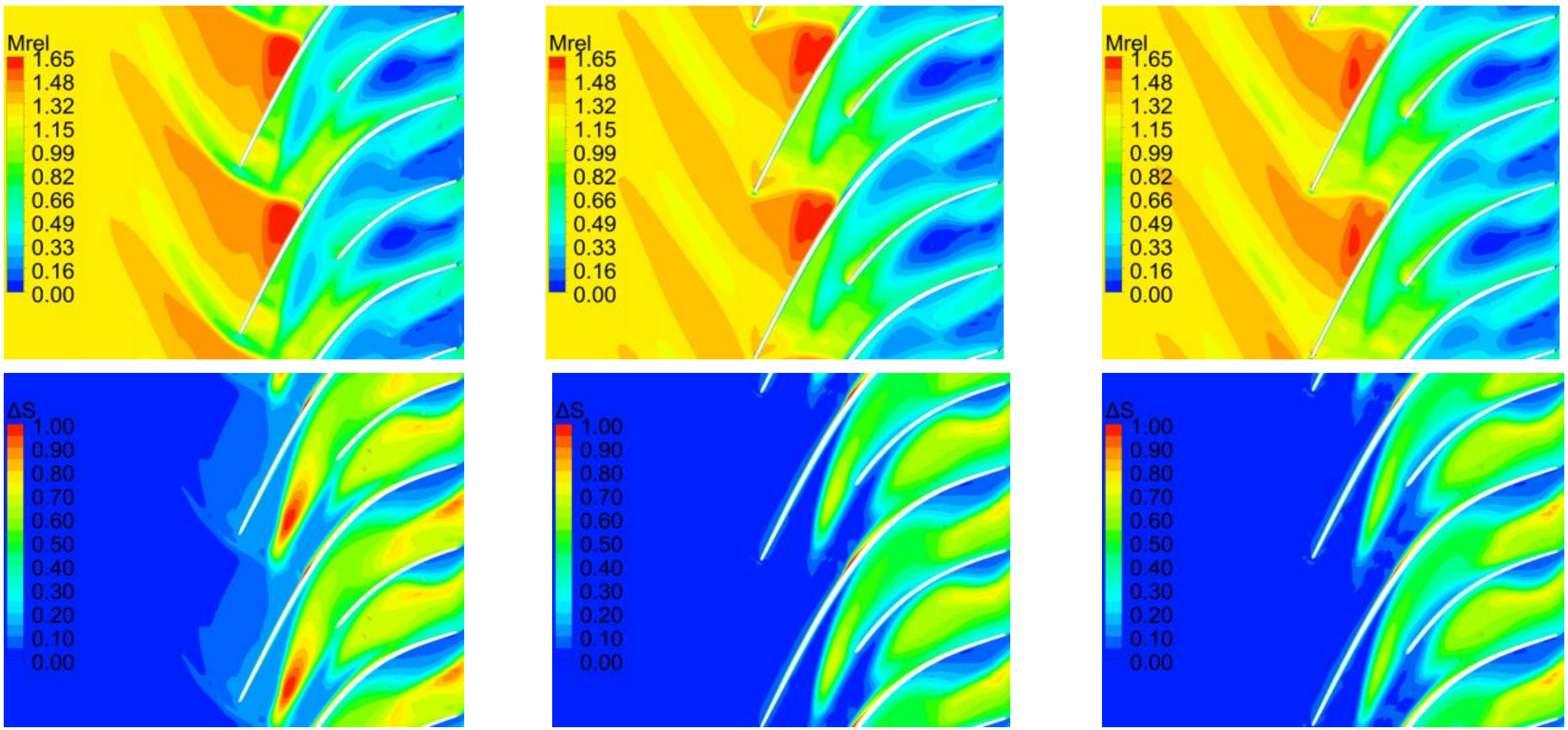


# Contours of $M_{rel}$ and Entropy at 95% span

- Swallowed shock with reduced losses at the tip of the swept impellers at design condition

Datum | Forward swept | Barrelled forward swept

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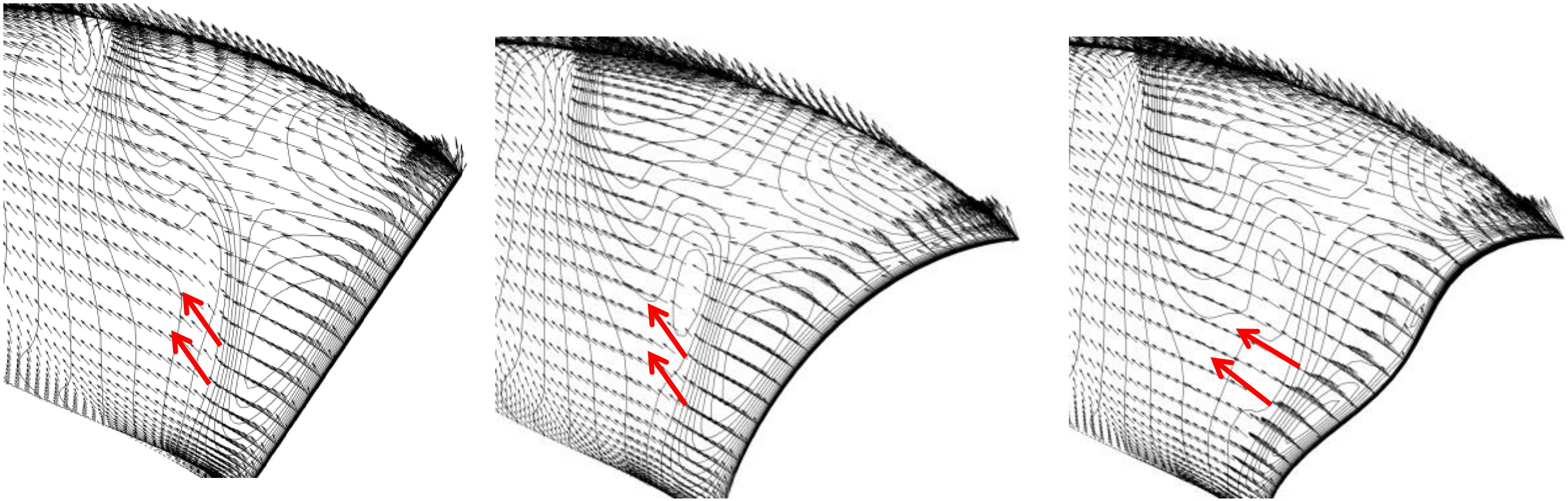
# Contours of static pressure and flow vectors near SS

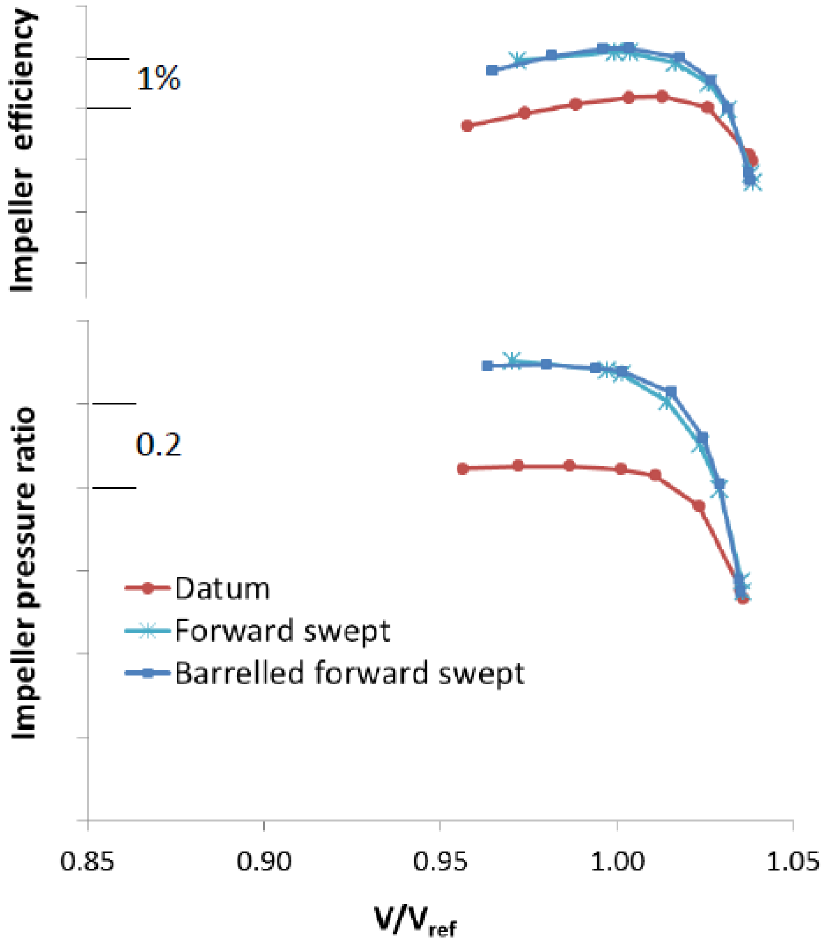
- Weaker shock and reduced radial migration of the boundary layer flow in the inner part of the barrelled forward swept impeller



Datum | Forward swept | Barrelled forward swept

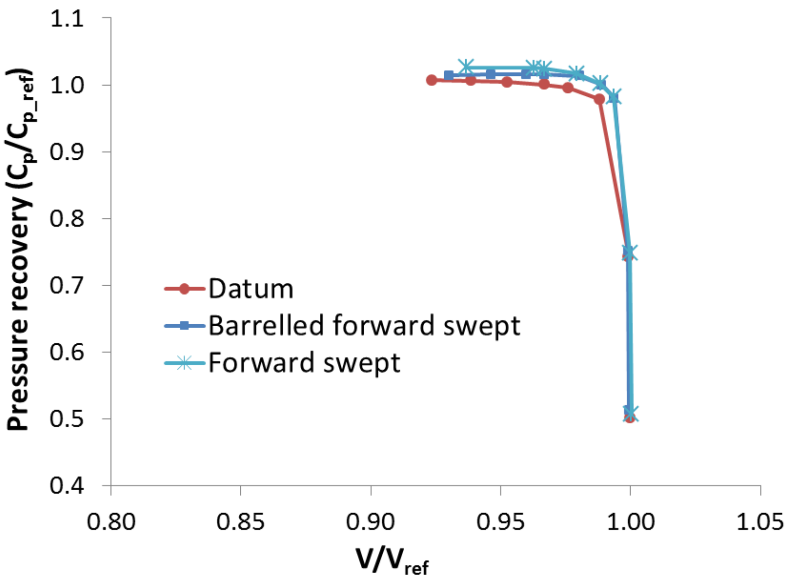
# Impeller performance

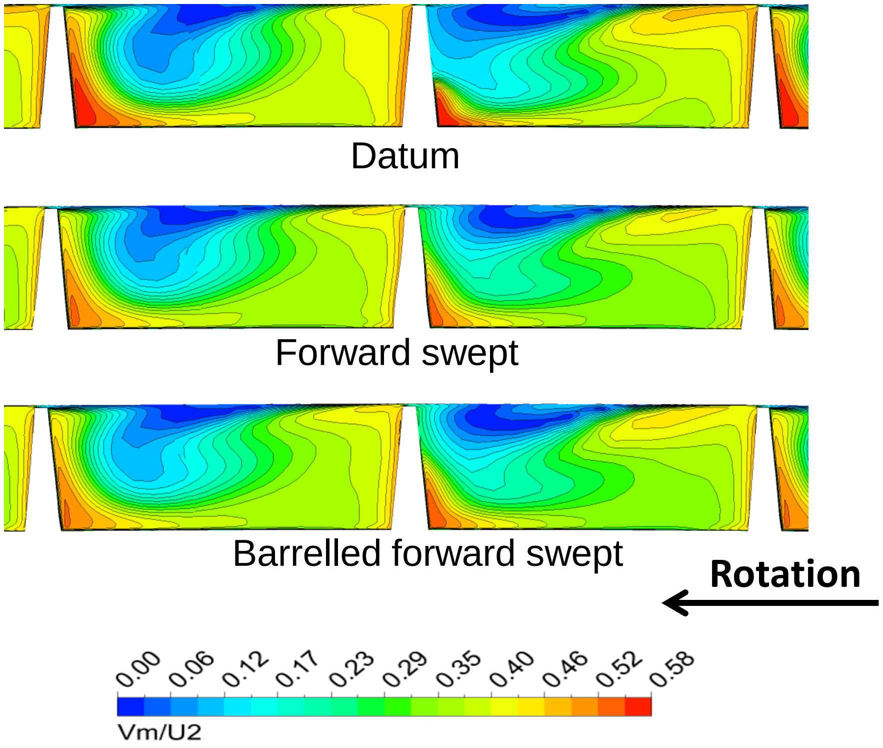
- No significant difference between the performance of the swept impellers
- Swept impellers showed about 1% higher total-to-total efficiency compared with the datum impeller
- No significant impact of the LE sweep on the operating range at the design speed



# Diffuser performance

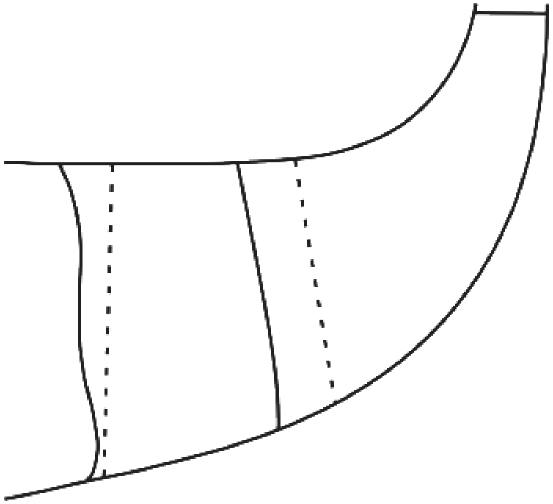
- Inducer design had relatively small effect on the flow at the impeller outlet
- Similar diffuser pressure recoveries



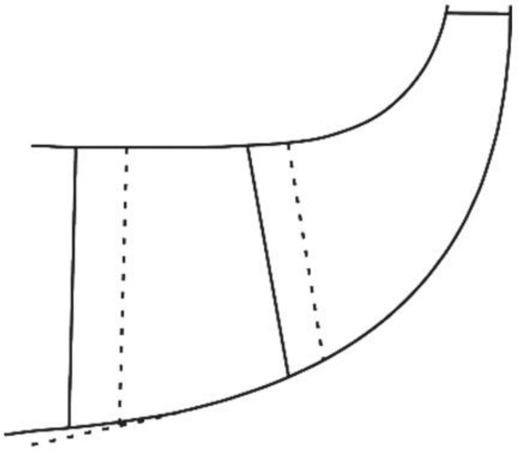
# Further studies

- Application of the LE sweep changes :
  - The length of the meridional chord at the tip
  - The distribution of the inlet angle and throat area along the span
  - The meridional profile of the LE
- An attempt has been made to study these effects in isolation



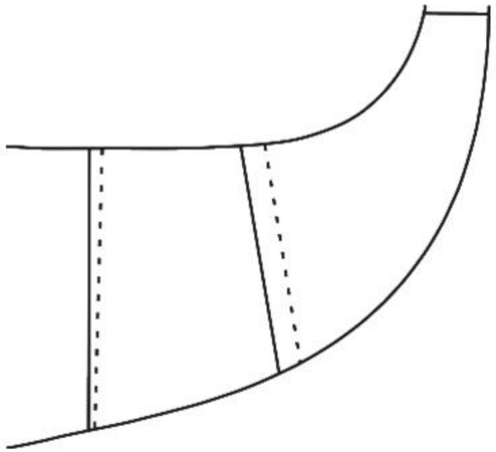
# Further studies

- <u>Ruled</u> **Extended chord** impeller
  - The tip section is the same as the swept impeller
  - The hub section is moved forward



Extended chord

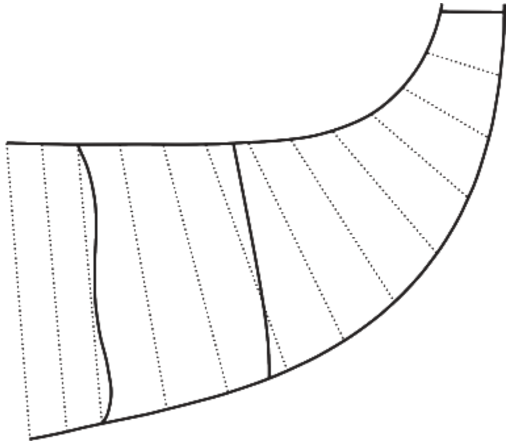
- <u>Free-form</u> **Unswept** impeller
  - The throat width and inlet angle distributions are the same as the Barrelled forward swept impeller



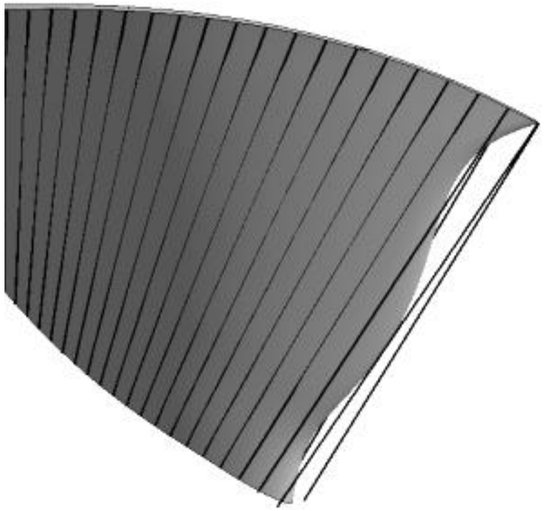
Unswept

# Further studies

- <u>Ruled</u> **Barrelled forward swept** impeller
  - Same tip profile as the free-form version
  - At the hub, blade thickness was adjusted to achieve the same flow capacity
  - 4% lower 1F frequency and 57% higher hub stress than the free-form version



Barrelled forward swept



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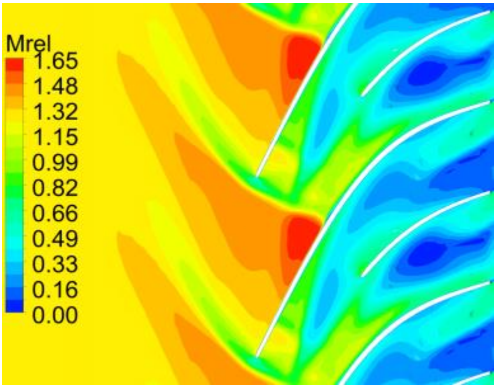
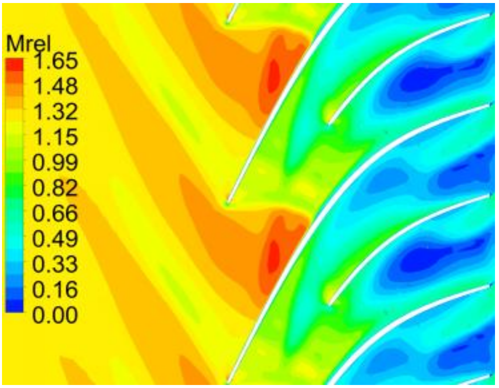
# Contours of $M_{rel}$ at 95% span

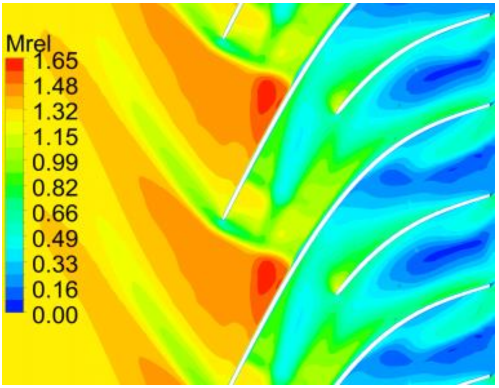
- Small effect of the chord length on the tip flow field
- Geometry in the inner part of the blade affects the flow at the tip
- LE sweep was less effective in the ruled impeller



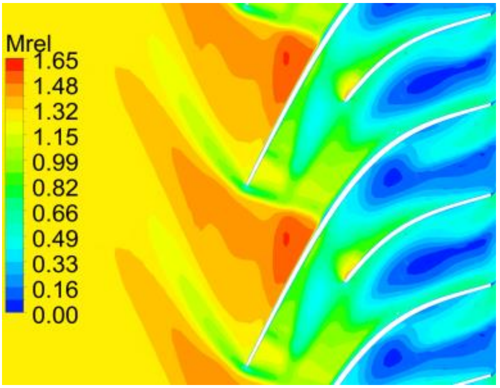
Datum



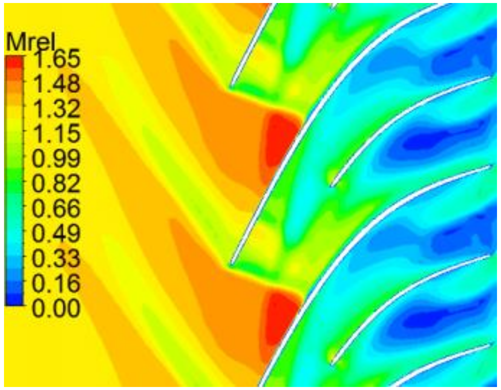
Barrelled swept



Extended chord



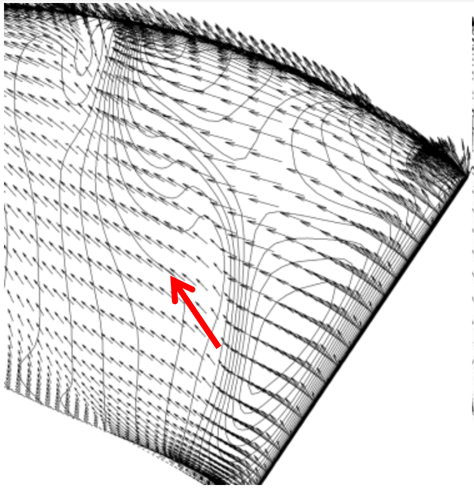
Unswept



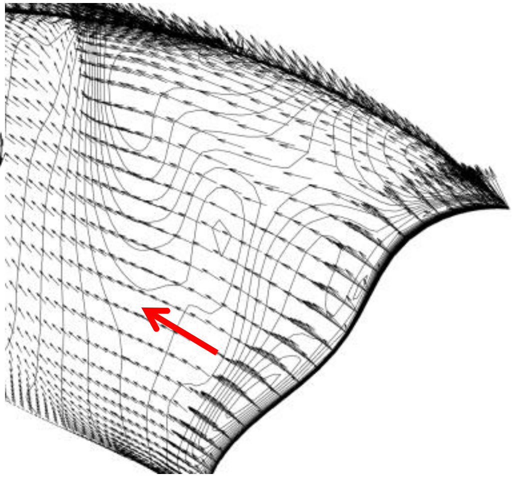
Ruled barrelled swept

# Contours of static pressure and flow vectors near SS

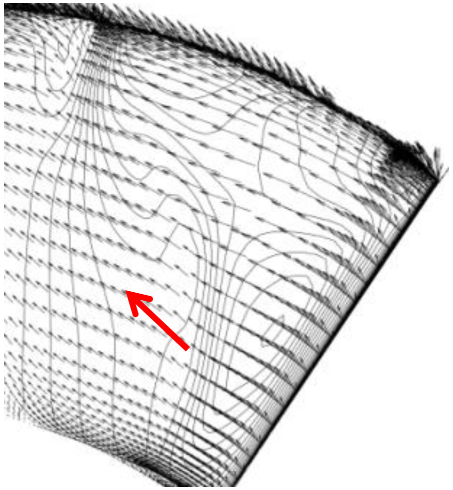
- Weaker shock at mid-span of the unswept impeller
- Strong shock at mid-span of the ruled swept impeller



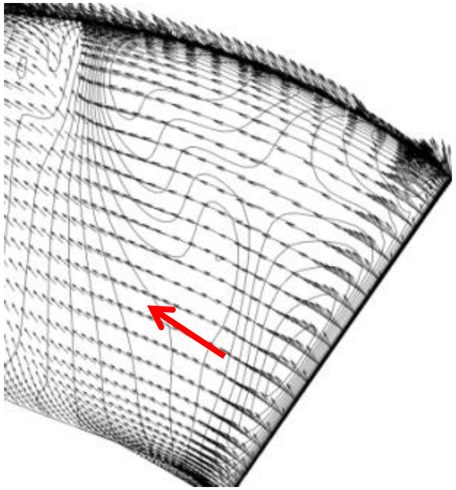
Datum



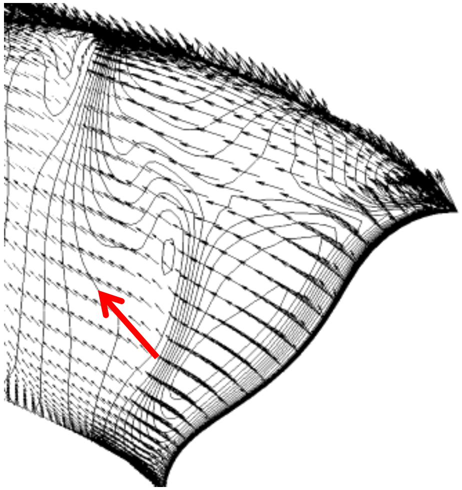
Barrelled swept



Extended chord



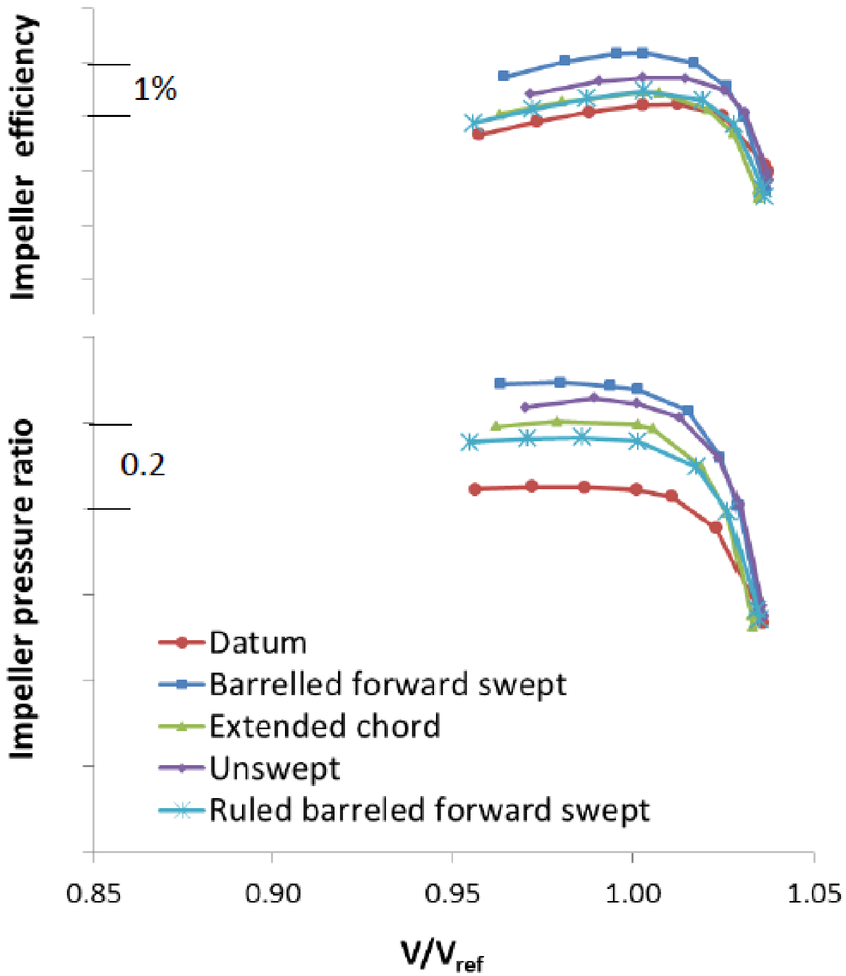
Unswept



Ruled barrelled swept

# Impeller performance

- Unswept impeller showed 0.5% higher efficiency than the datum ruled design
- Relatively smaller effect of the chord length and LE sweep when applied to a ruled design
- Leading edge sweep should be viewed as a design parameter whose effects depend on other geometrical parameters



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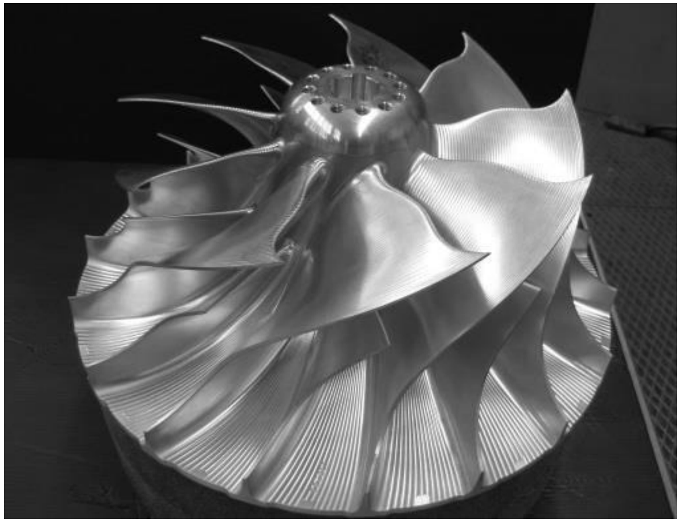
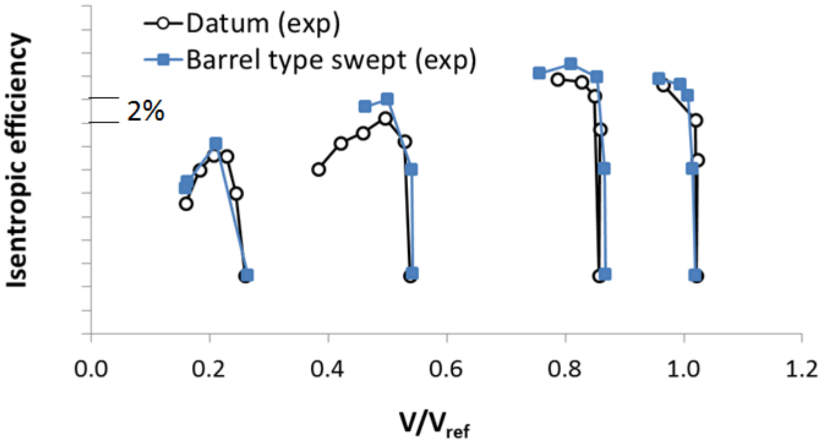
# Tested impellers

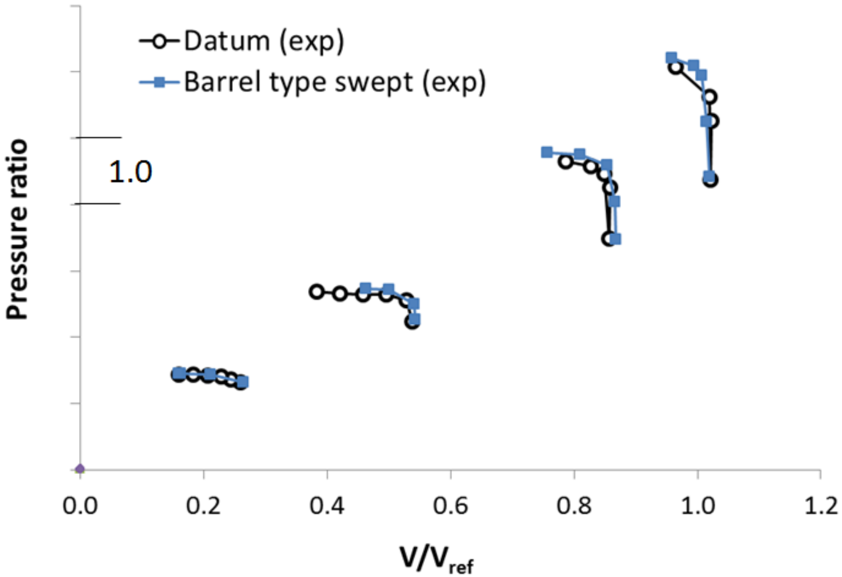
- The Datum and the Barrelled forward swept impellers were manufactured and tested at 100%, 90%, 70% and 40% of the design speed
- The impellers were tested with and **without** casing treatment
- Same stationary components were used



# Measured performances

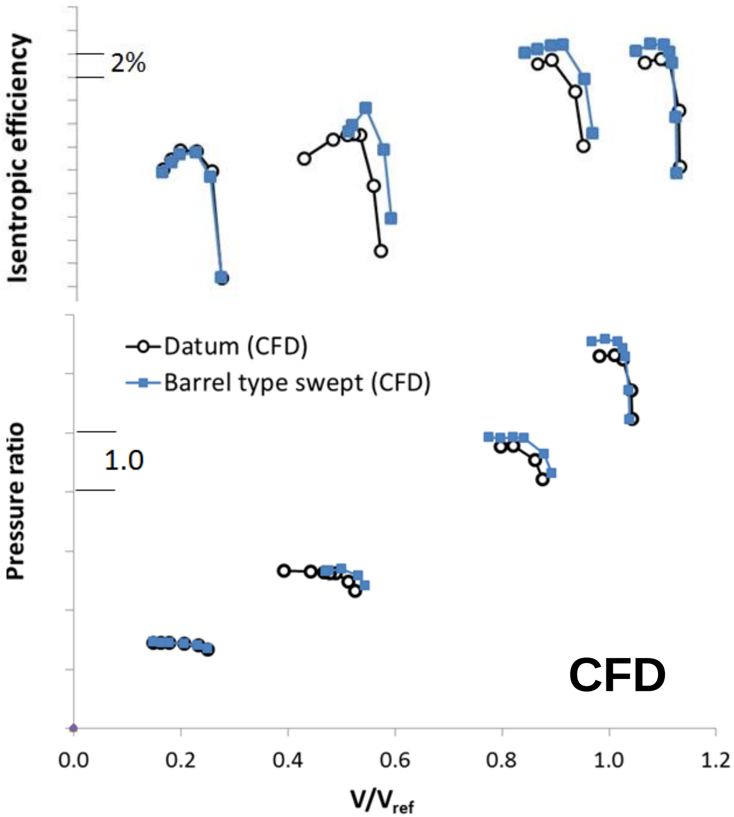
- Stage with the swept impeller shows:
  - 0.5% higher efficiency and same range at **100%speed**
  - 1.2% higher efficiency and 5.2% wider range at **90% speed**
  - 1.6% higher efficiency but 17% narrower range **70% speed**
  - 0.9% higher efficiency and the same range at **40% speed**

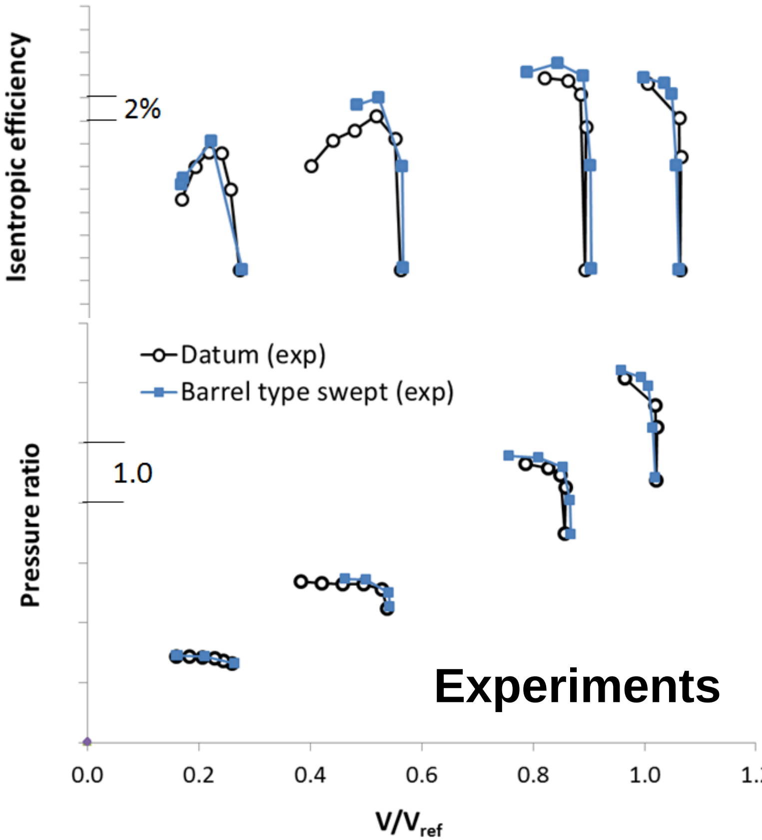


# CFD vs. Measured performances

- Calculations suggest 1% improvement for swept impeller at design speed
- Trend is captured well especially at part speed

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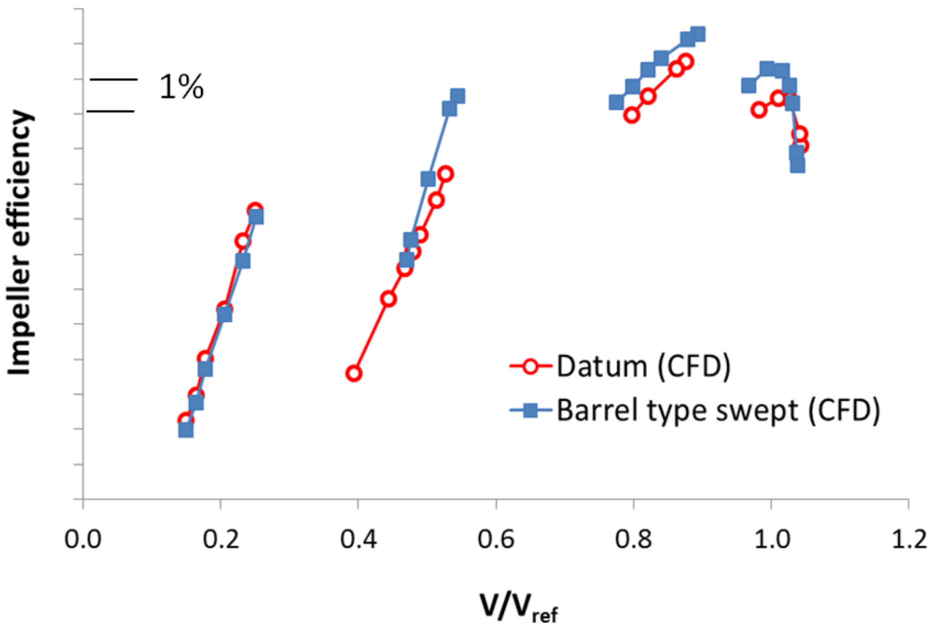
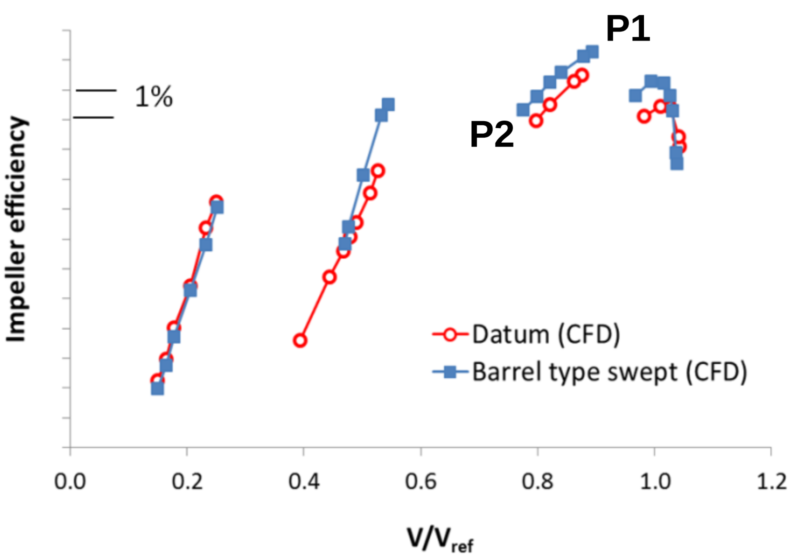
# Impeller only performance

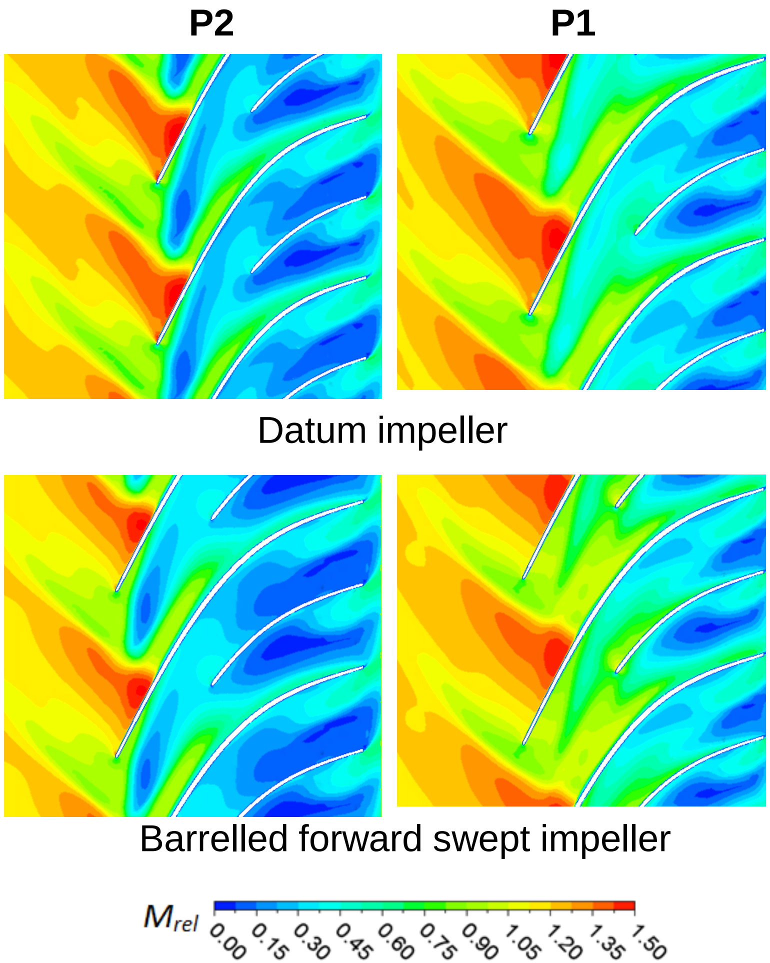
- Diffuser is matched to the impeller at the design speed
- At part speed, the impeller is forced (by diffuser choking) to operate on the left hand side of its peak efficiency



# 90% of the design speed

- Similar flow fields at the tip
- Reduced loading and weaker shock at the tip of the swept impeller results in higher efficiency levels

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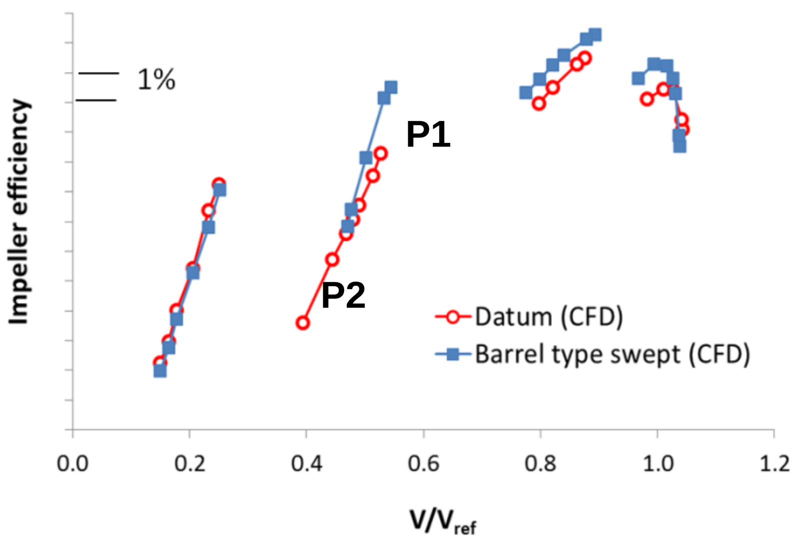
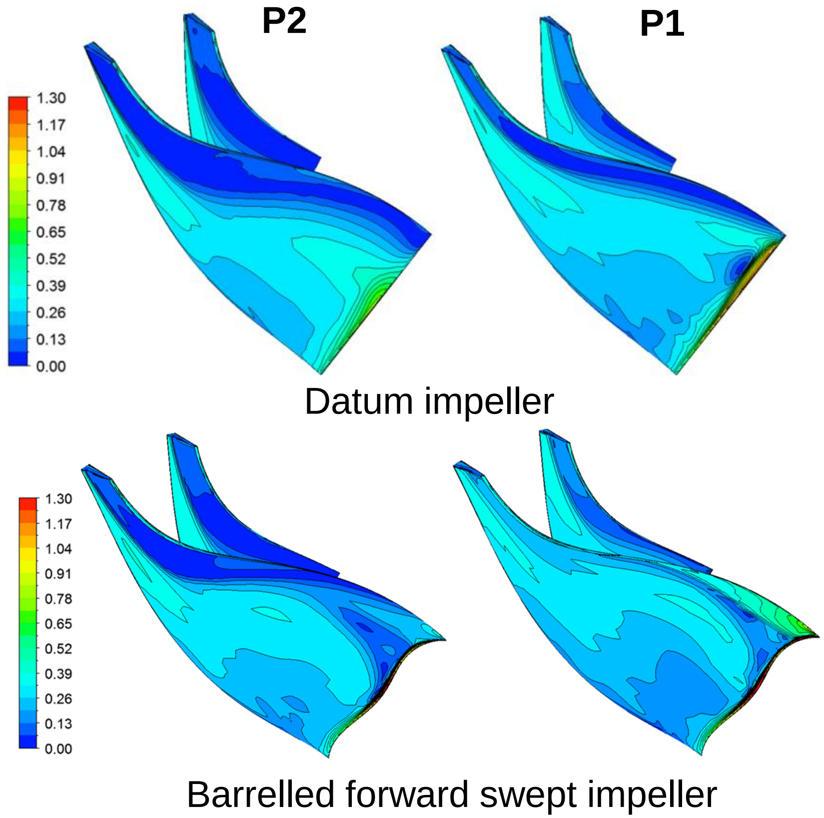
# 70% of the design speed

- **Datum impeller:** Conventional inlet recirculation at the tip
- **Swept impeller:** Separation from 50%-80% span near LE at P1

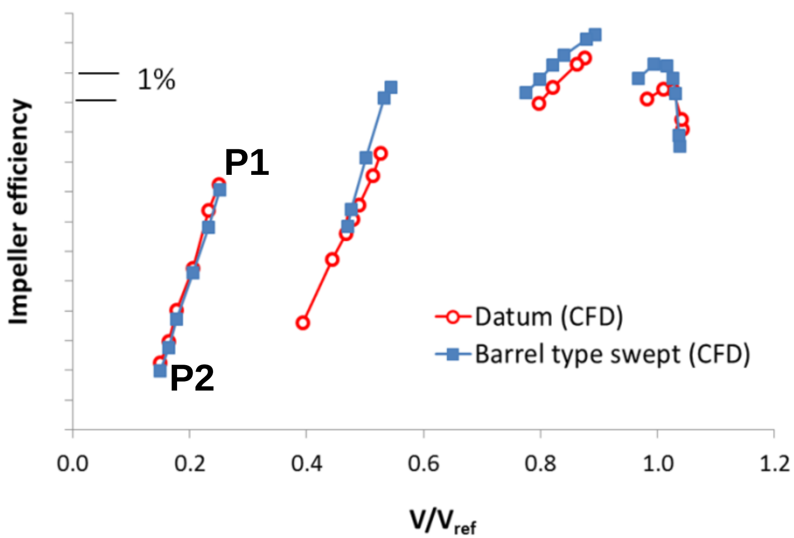
  Large separation in the upper part of the span as the mass flow is reduced

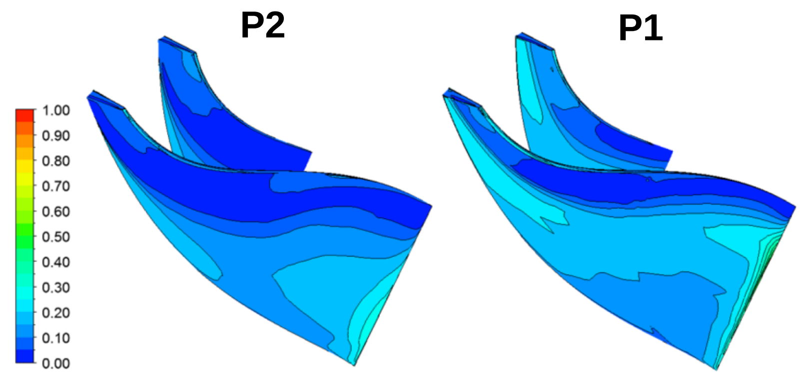


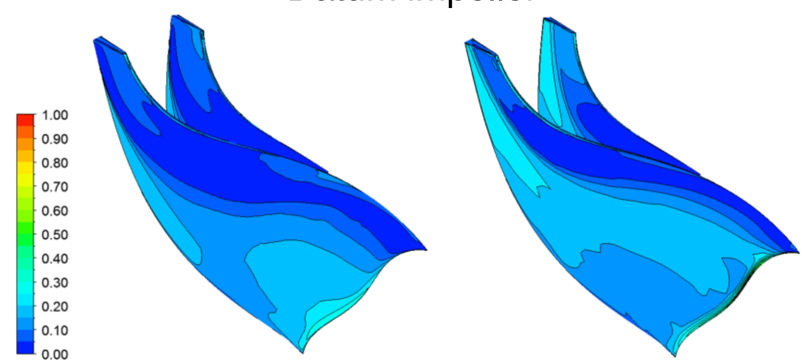
# 40% of the design speed

- Conventional inlet recirculation at the tip of the both datum and swept impellers
- No significant difference in performance of the impellers




Datum impeller




Barrelled forward swept impeller

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# Conclusions

- A barrelled forward sweep of the leading edge, offered better mechanical properties while maintaining the performance benefits of the forward swept impeller
- The observed performance improvements are combination effects of LE sweep and other geometrical parameters such as angle and throat area distributions
- The swept impeller showed 0.5% to 1.6% higher efficiency levels compared with the datum impeller depending on the operating speed

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