# ORGANIC RANKINE CYCLE TURBINE FOR EXHAUST ENERGY RECOVERY IN A HEAVY TRUCK ENGINE

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# Outline

| Context | Development program |
| --- | --- |

## Context

- Organic Rankine cycle uses a refrigerant working fluid that:
  - ❑ Is heated by engine exhaust gas
  - ❑ Expands through a turbine connected (through gearing) to the engine shaft
- A novel turbine design is required because:
  - ❑ The operating conditions (speed, flow, pressure ratio, etc) are quite different from those of conventional turbocharger turbines
  - ❑ The fluid properties of the refrigerant are different from those of air, exhaust gas, etc

## Development program

- Investigate a range of turbine architectures to determine suitability, i.e.
  - ❑ Performance
  - ❑ Size / packaging
  - ❑ Manufacturability
- Down-select to the most promising solution
- Detail design, manufacture, and prototype test

# Design specifications

- Turbine design point rotational speed is set by typical engine operating speed and consideration of mechanical coupling between turbine and engine

**Turbine shaft speeds and gear ratios at B100 condition**

| Turbine Rotational Speed | Gear Ratio |
|---|---|
| 40k rpm | 26.7:1 |
| 50k rpm | 33.3:1 |
| 60k rpm | 40.0:1 |
| 84k rpm | 56.0:1 |

**Ideal Solution**

- ✓ Maximum efficiency
- ✓ Small footprint
- ✓ Minimum shaft speed



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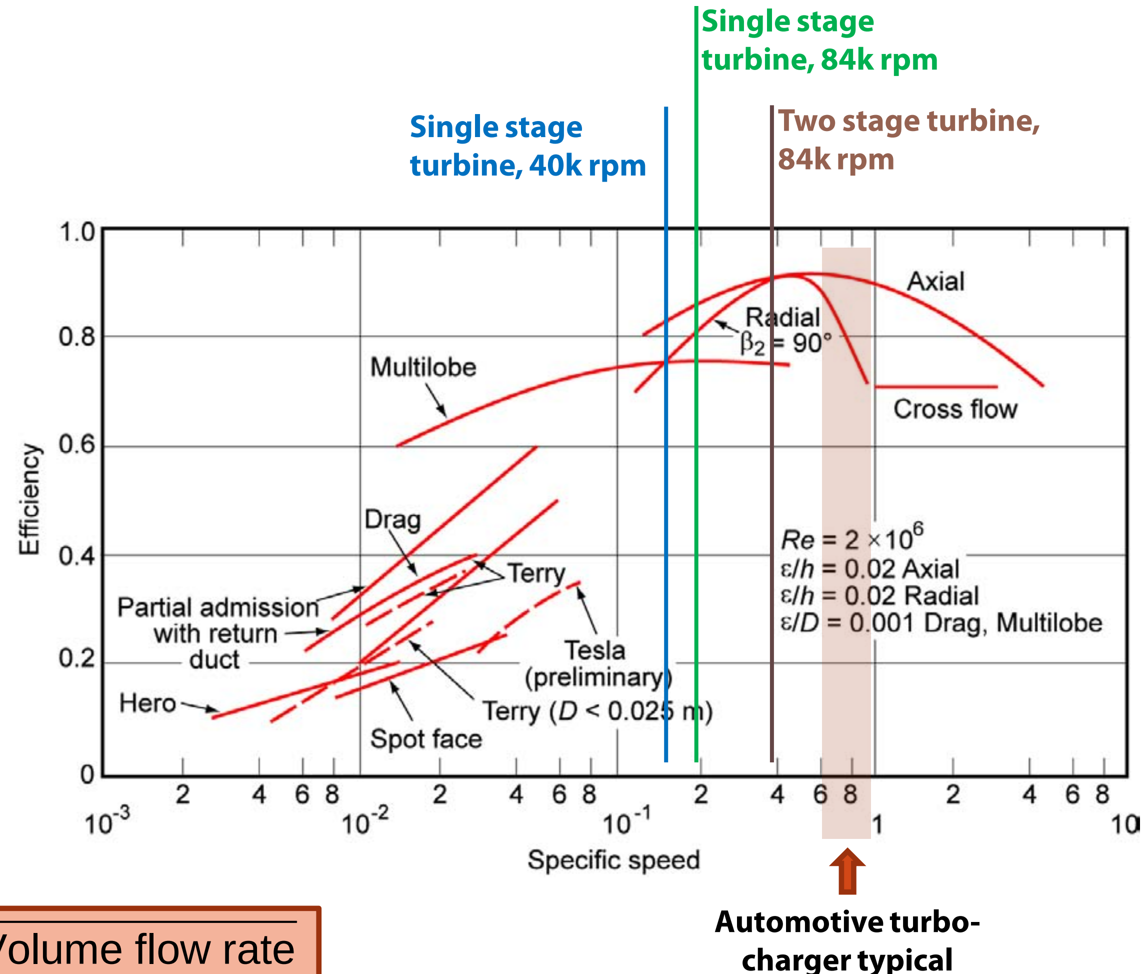
# Turbine selection

- ***Specific speed*** is a useful way to characterize turbines
- There are good, experience-based, rules
- Design conditions demand specific speeds that are well below those of typical automotive turbochargers




$$\text{Specific speed} = \frac{\text{Speed} \times \sqrt{\text{Volume flow rate}}}{(\text{Specific work output})^{3/4}}$$





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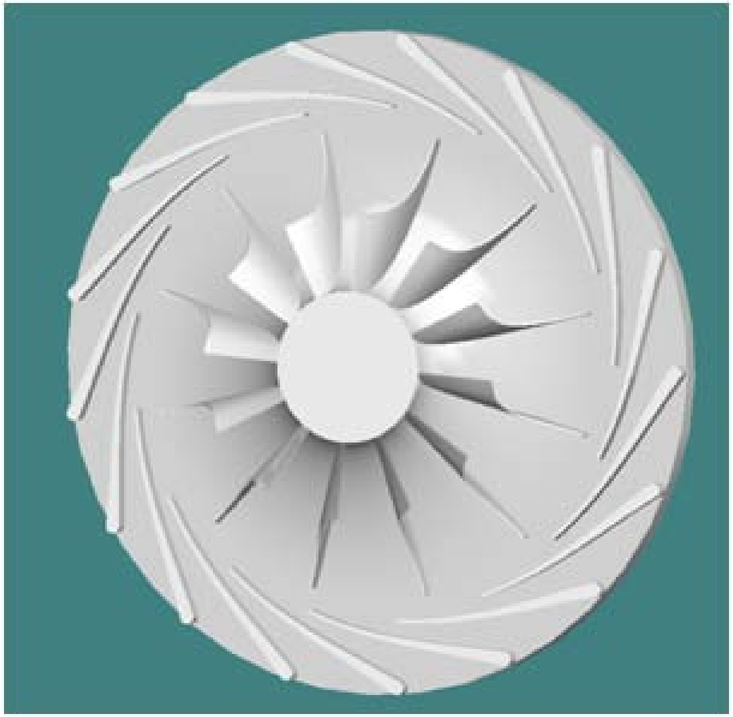
# Conceptual designs

- Single stage radial turbine
- Two stage axial turbine
- Single stage axial turbine

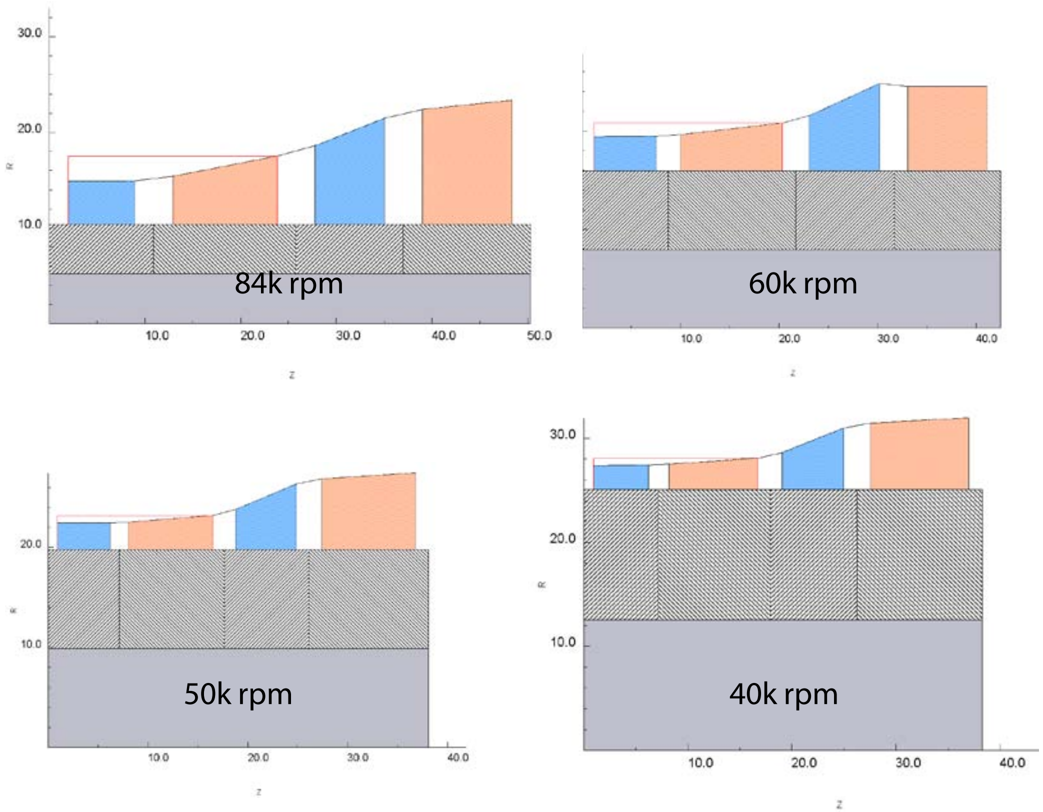
- In each case, consider a range of speeds from 40,000-84,000 rpm

# Single stage radial turbine



- Efficiency increases with speed of rotation
- Size decreases with speed of rotation
- Even at the highest speed, the ratio of passage height to rotor radius is very small

# Two-stage axial turbine




- Blade height decreases and tip radius increases as turbine speed is reduced to maintain similar tip speeds
- Efficiency increases with speed of rotation
- Significant change in wheel speed across blade span: variable section blades are required for all two-stage designs
- Possible to design blades to be flank-millable with small impact on efficiency



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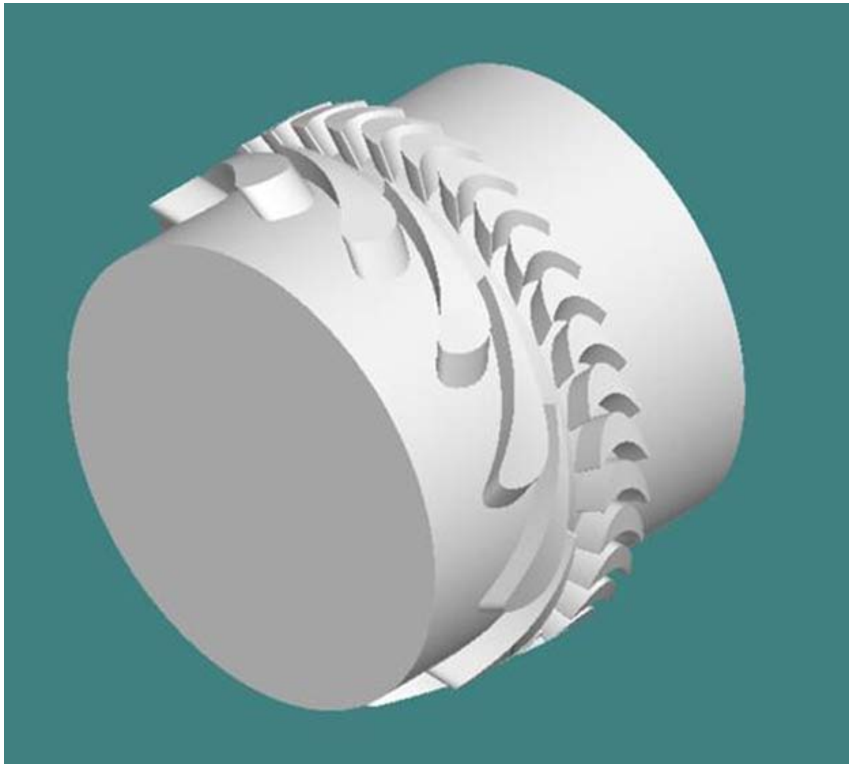
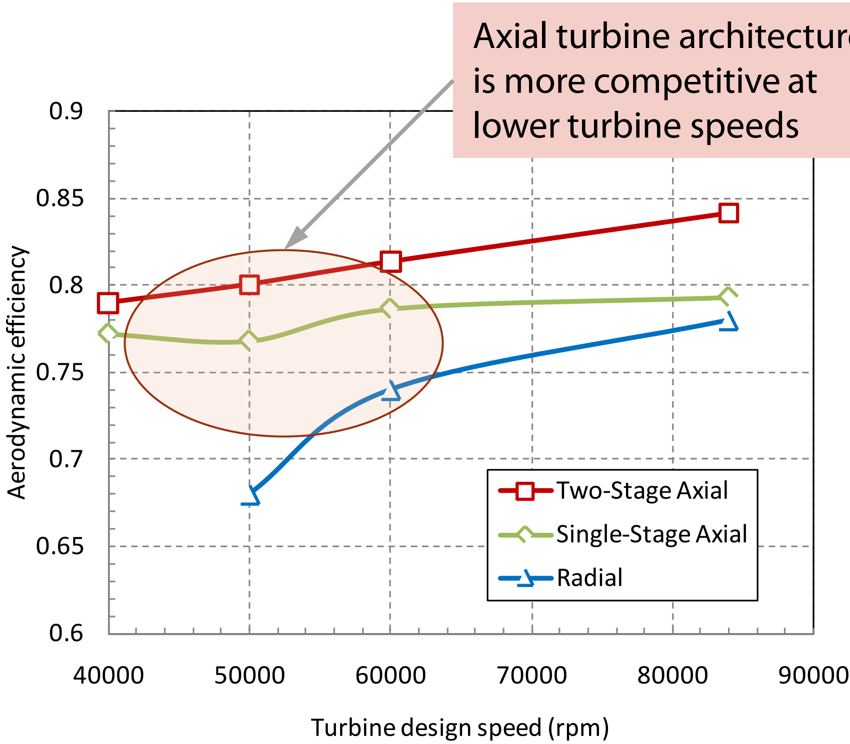
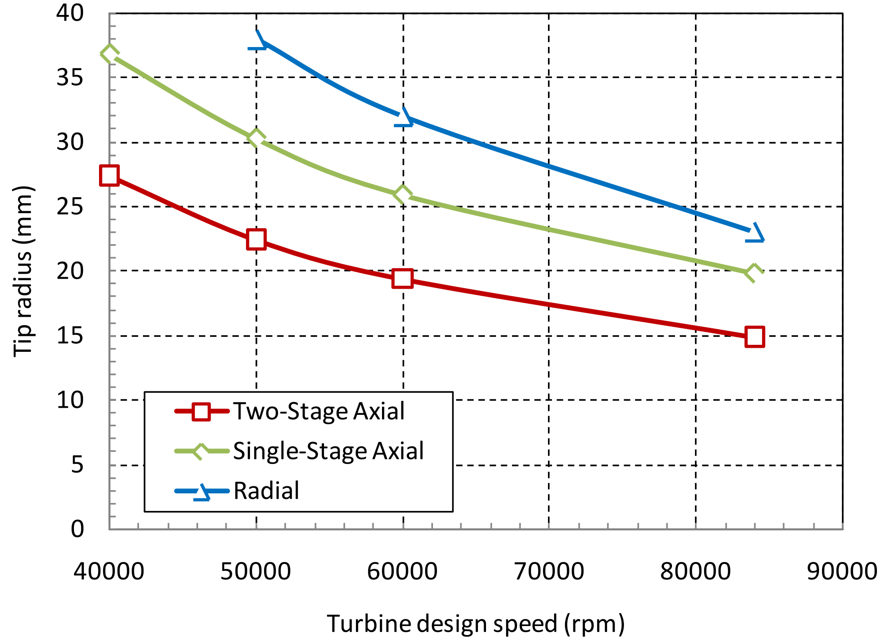
# Single stage axial turbine



- Tip radius decreases and blade height increases with speed
- Efficiency increases with speed
- Stator blades are transonic: exit Mach number = 1.5 – 1.7
- Constant section blades are acceptable (reduces manufacturing costs)

# Performance summary

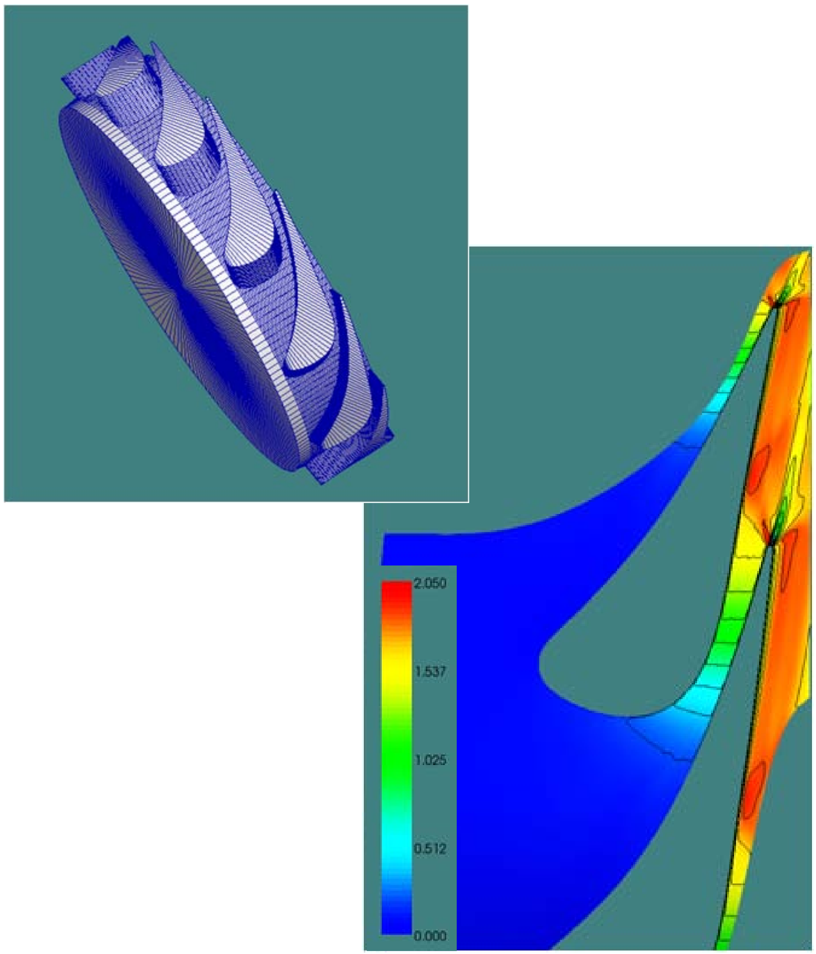


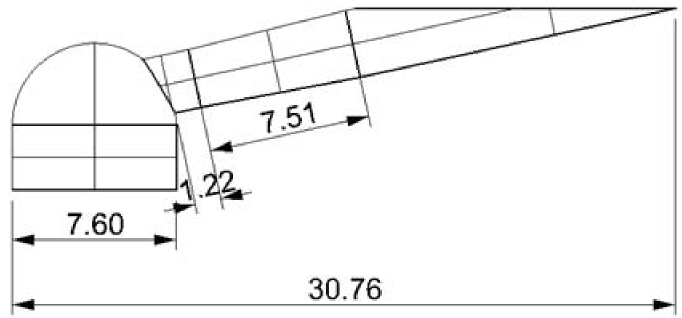

- Two-stage turbine has potential performance, but too complicated
- Down-select to ***single stage axial turbine***

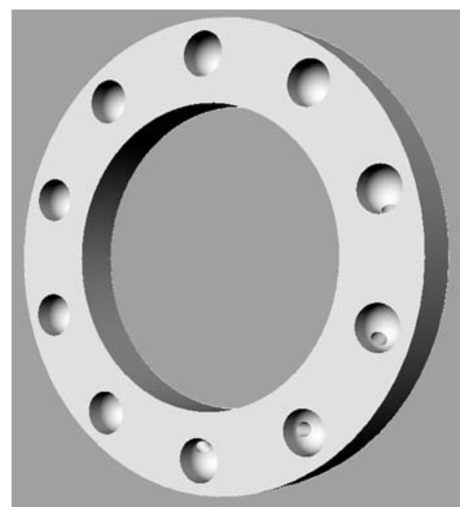
# Supersonic nozzle options

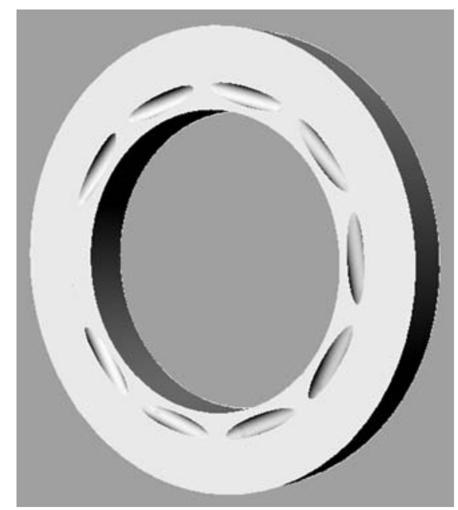
- Bladed, con-di nozzle




- Drilled and reamed conical nozzle









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# Supersonic nozzle options

## Bladed, con-di nozzle

- Better performance (+5 pt efficiency at maximum load conditions)
- More expensive to manufacture. EDM/ECM is required
- Throat width ≅ 1 mm
  - Design and performance is very sensitive to manufacturing tolerances
  - Testing will be required to establish final design

## Drilled, conical nozzle

- Circumferentially non-uniform flow entering rotor makes performance prediction difficult. Some experience required
- Cheaper to manufacture and easier to hold throat area tolerances
- Design is compromised by size envelope, and requires a different inlet duct arrangement



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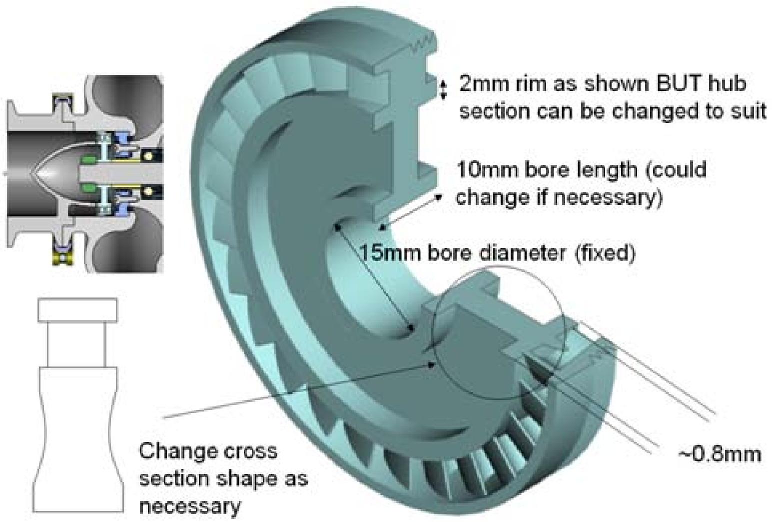
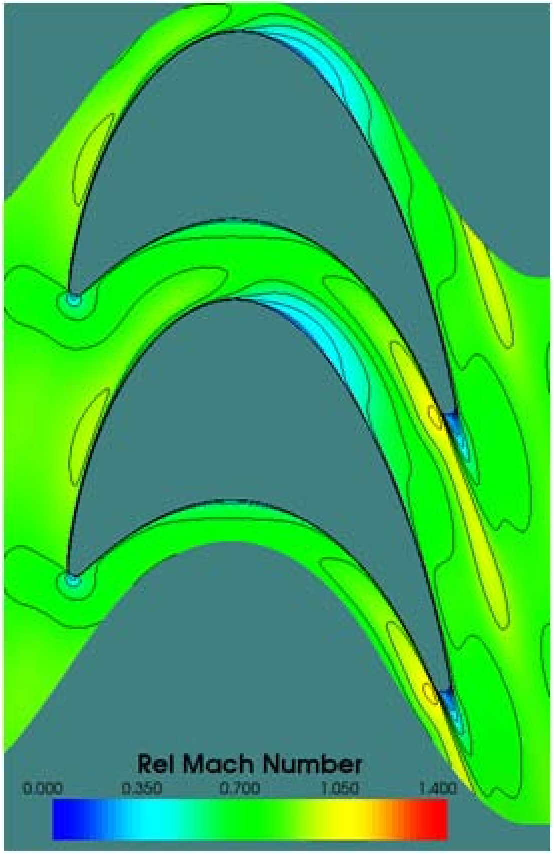
# Rotor design

- Single stage architecture demands very high flow turning, but this can be managed with proper aero design
- Shrouded rotor is required to reduce tip leakage losses, which have a large impact on efficiency in a small turbine



# Conclusions

- The ORC demands a unique turbine solution, and conventional turbocharger turbine design has little relevance
- The turbine is highly loaded, with a supersonic nozzle
- Two nozzle variants were developed to function with a common shrouded rotor
    - Full admission arc airfoil nozzle
    - Partial admission drilled nozzle
- The turbine performance is very sensitive to rotor leakage flow and proper treatment of this flow is critical
- The airfoil nozzle turbine is predicted to achieve satisfactory efficiency with proper sealing solutions