DEVELOPMENT OF A 300 kW_e INTEGRATED AXIAL TURBINE AND GENERATOR FOR ORC APPLICATIONS

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Concepts NREC (*CN*)

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Challenges of Existing Non-Hermetic ORC Systems

- **Shaft seals**
  - Generally accepted to be the least reliable component in rotating machinery
  - Working fluid leakage is expensive
    - Possibility of fire with flammable refrigerants
    - Must measure and log refrigerant levels
    - Leaked refrigerant replacement is expensive
  - Requires shaft seal pressure control system, temperature monitors, leak monitors, etc.
  - High inspection and maintenance costs; periodic seal replacement
  - Mechanical losses: 1–2%
- **Gearbox**
  - Inspection and maintenance costs
  - Mechanical losses: ≈4%
- **Couplings**
  - Inspection and maintenance costs
- **Lubricated bearings**
  - Mechanical losses: ≈2%
  - Requires oil system
  - High-speed lubricated bearings have rotordynamics complications
- **Oil systems**
  - Use of oil limits the maximum temperature of the heat source
    - High temperatures degrade oil
    - Limits applicability of ORC technology
  - Requires oil separator, filter, strainer, and cooler
  - Requires periodic oil filter and strainer changes
  - Parasitic power losses: ≈2%
  - High maintenance issues and costs
    - Must measure and log oil levels
    - Periodic oil additions and changes
    - Periodic oil sampling and analysis (moisture, acidity, and metal content)
- **Instrumentation**
  - Separate vibration probes and proximity sensors are usually required to monitor turbine and/or gearbox shaft vibration levels on high-speed rotary shafts
- **Turbine matching**
  - Standardized turbine designs of many ORC systems are a poor match for many applications

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Effect of Stage Reaction on Turbine Design

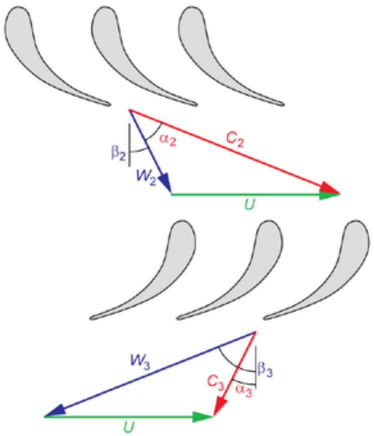
- **Customized ORC turbine designs lead to optimum system efficiency**
- **Reaction (Λ) is a very important parameter in turbine design, fundamentally influencing:**
  - Turbine performance characteristics
  - Stator and rotor design
- **Choosing the right reaction is the key to successful design**
- **Assuming constant blade speed and meridional velocity, and neglecting internal losses, for a stage of arbitrary reaction, it can be shown that the stage efficiency and specific work output are:**

$$\eta = 2\upsilon\left\{(1-\Lambda)^{1/2}\sin\alpha_2 + \left[(1-\Lambda)\sin^2\alpha_2 + \upsilon^2 - 2\upsilon(1-\Lambda)^{1/2}\sin\alpha_2 + \Lambda\right]^{1/2} - \upsilon\right\}$$

$$\frac{W_x}{U^2} = \frac{\sqrt{1-\Lambda}}{\Lambda}\sin\alpha_2 + \left[\frac{1-\Lambda}{\upsilon^2}\sin^2\alpha_2 + 1 - 2\frac{\sqrt{1-\Lambda}}{\Lambda}\sin\alpha_2 + \frac{\Lambda}{\upsilon^2}\right]^{1/2} - 1$$

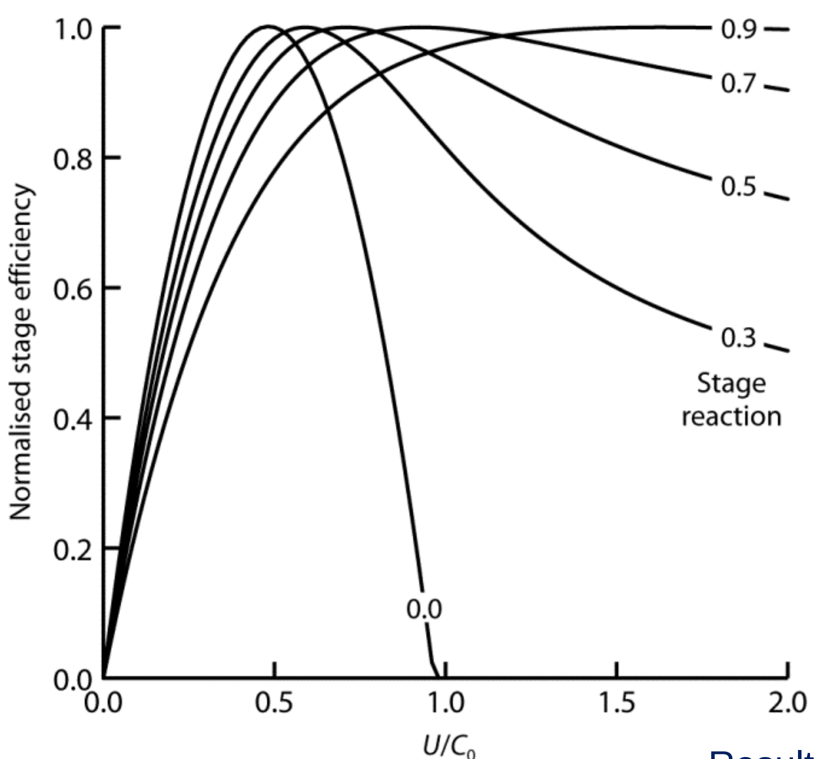
Where:

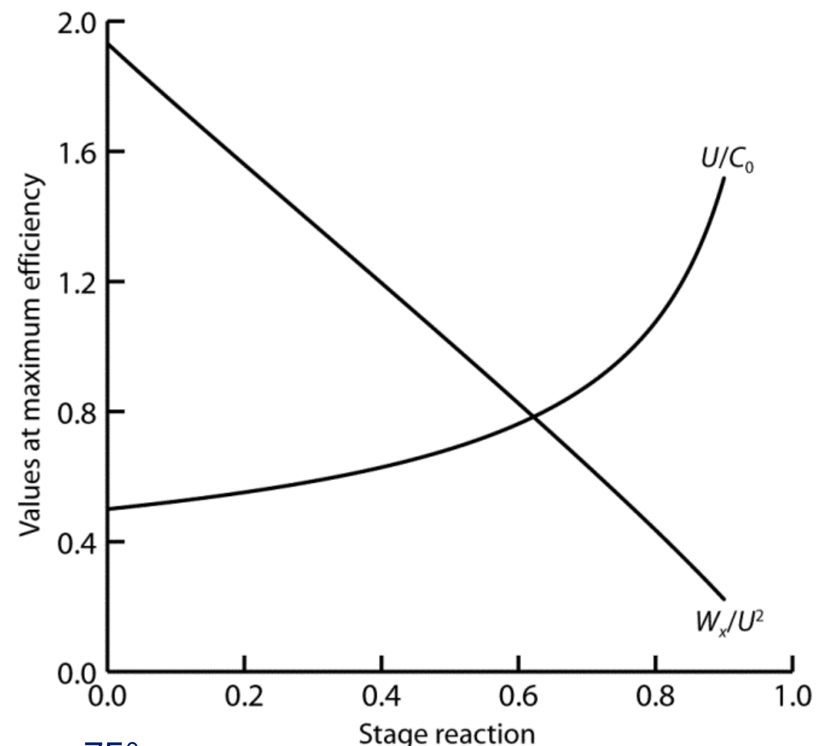
Λ = Reaction = $\Delta h_{Rotor} / \Delta h_{Stage,\ Stagnation\ Conditions}$
η = Stage Efficiency
W_x = Work, Axial Component
U = Blade Speed
C_2 = Absolute Velocity, Rotor Stage Inlet
W_2 = Relative Velocity, Rotor Stage Inlet
υ = Velocity Ratio U/C_x
α_2 = Absolute Flow Angle, Rotor Stage Inlet
β_2 = Relative Flow Angle, Rotor Stage Inlet



Stage Reaction Selection Affects Turbine Performance Characteristics

- **Low-Reaction Turbines are generally favored for high-pressure ratio, low-flow applications (i.e., ORC systems), but the choice of reaction depends on many effects – structural, manufacturing, and aero performance**
- **Reaction is also influenced by the priorities of high efficiency (→ medium reaction) and high specific work output (→ low reaction)**





Results for $\alpha_2 = 75°$

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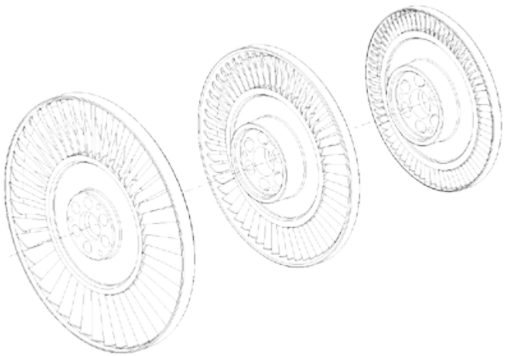
CN's Organic Rankine Cycle Solution Addresses Technical and Economic Issues

- **ORC Turbine Generator Unit (TGU)**
  - Consists of: turbine, generator, generator controls, and power electronics
- **Hermetically sealed 20,000 rpm TGU**
  - Axial turbine directly mounted to generator shaft
  - No shaft seal, gearbox, or coupling
  - Oil-free design
- **Magnetic bearings**
  - No lubricated bearings
  - Inherent radial vibrational monitoring



- **Generator is evaporatively-cooled by refrigerant – patent pending**
- **State-of-the-art, variable-frequency permanent-magnet generator and controls**
  - No speed governor
- **Patent-pending, modular turbine flow path and system**
  - Can easily customize a 1- to 4-stage, axial nozzle-rotor subassembly cartridge
  - Allows use with a wide variety of working fluids and pressure ratios
  - Can meet a customer's exact cycle requirements
  - Radial turbine option depending on fluid enthalpy and pressure ratio

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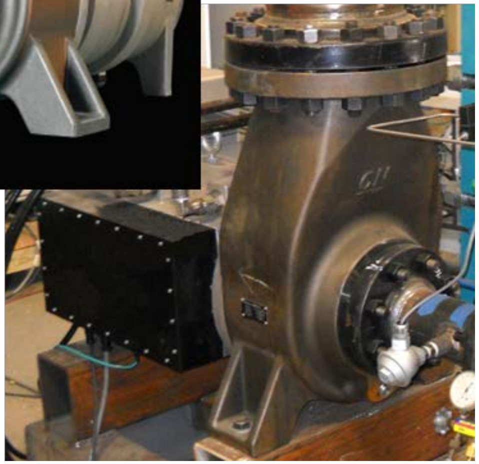
CN's CN300 ORC TGU Can Operate Over a Range of Conditions

- **Initial member of *CN*'s ORC TGU product line**
- **Designed using *CN*'s Agile Engineering Design System®**
- **Gross power range**
  - 150–330 kWe
- **TGU speed**
  - 20,000 rpm
- **Turbine inlet temperature range**
  - 80–220°C
- **Turbine casing inlet pressure rating**
  - 40 Bar (Absolute)
- **Turbine casing outlet pressure rating**
  - 14 Bar (Absolute)
- **Turbine pressure ratio range**
  - 2:1–25:1
- **Working fluid compatibility**
  - R112, R113, R114, R134a, R236fa, R245fa
- **TGU size**
  - 1.07 m x 0.62 m x 0.87 m
  - 544 kg (1200 pounds)
- **Electrical details**
  - 380–480 VAC, 3-phase, 50–60 Hz

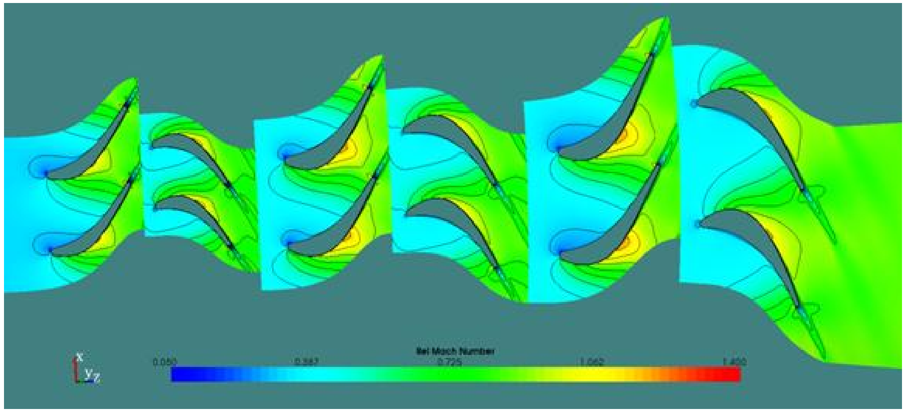


Patent Pending

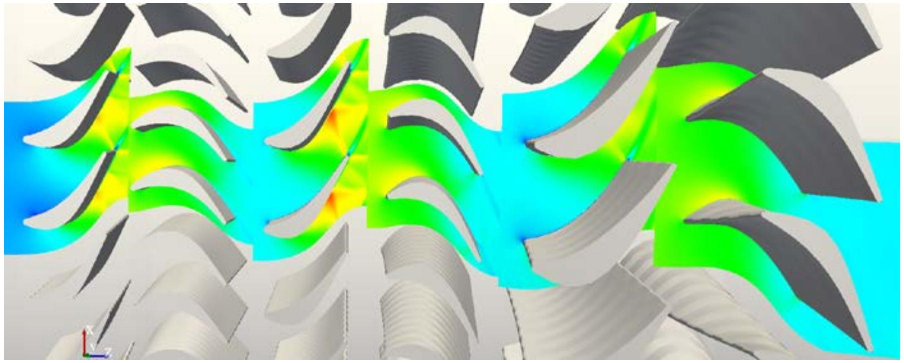
Agile Engineering Design System is a registered trademark of Concepts ETI, Inc.

CN300 Uses Advanced Aerodynamic Design to Optimize Performance

- ***CN*'s Agile Engineering Design System**
  - Ideally suited for ORC turbine applications
  - Computer-Aided Engineering (CAE) → Computer-Aided Manufacturing (CAM)
- **CAE: Aerodynamic analysis**
  - Uses *CN*'s AxCent® software
  - For complex blade geometries
  - Interfaces with third-party optimizers
- **Multistage 3D CFD analysis**
  - Allows accurate performance prediction of entire unit
  - Allows improved stage matching
  - Better resolution of 3D effects and secondary flows
- **Custom, optimized design**
  - Optimized for each customer application
  - 1 to 4 expansion stages
  - Choice of refrigerants and conditions
- **Calculate performance of existing CN300 design with new customer conditions**
  - Avoid nonrecurrent engineering



Typical CFD Turbine Analysis Results



Mach Number Contours Through Flow Path

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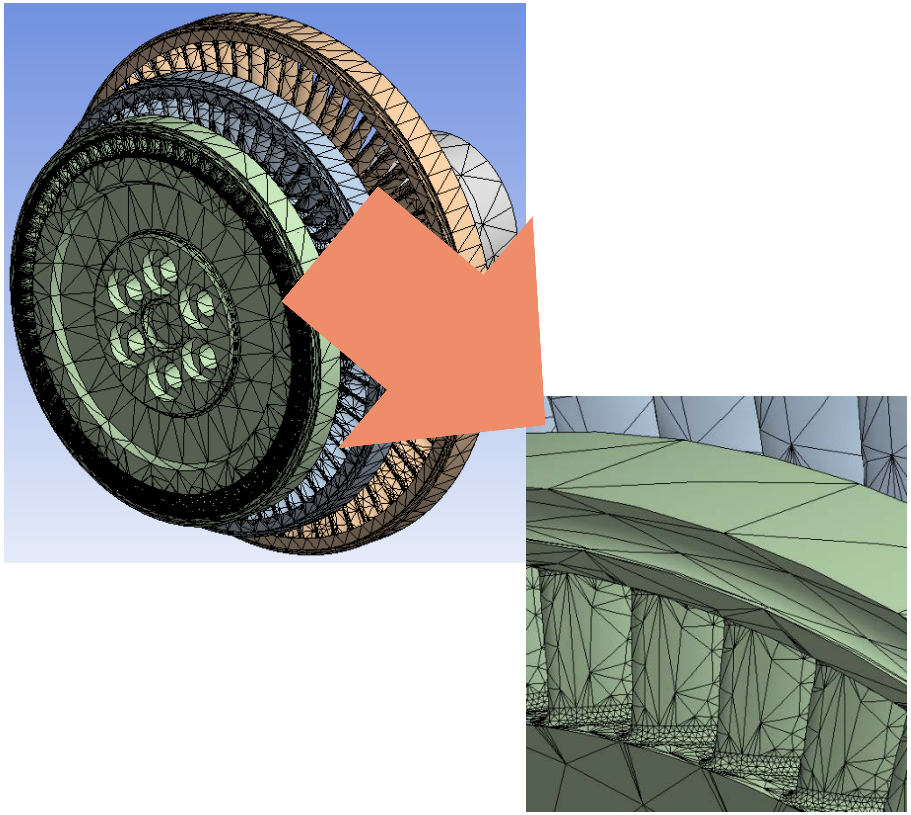
CN300 Mechanical Design Uses Advanced Design Techniques

- **CAE-based Finite Element Analysis (FEA)**
  - FEA models created in ANSYS® Workbench™
  - Blade stacking of 2D cross sections
  - Blade restaggering around an arbitrary axis
  - Bowed blading defined by hub-to-shroud bow profiles
  - And more
- **Also developed specifications and methodology for Selective Laser Sintering (SLS) process**
  - For rotors and stators
  - Good alternative to 5-axis machining
  - Complexity of airfoil shape is not limited by machining (i.e., flank milling vs. point milling)



Mesh and Mesh Detail for FEA

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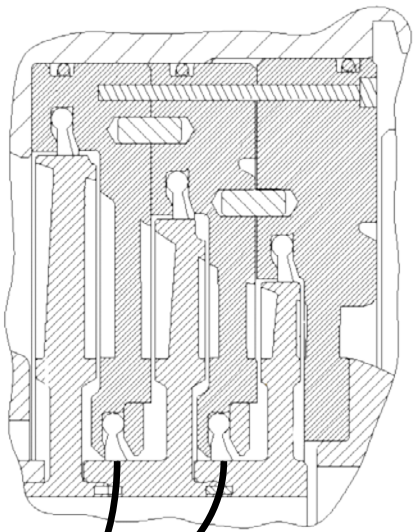
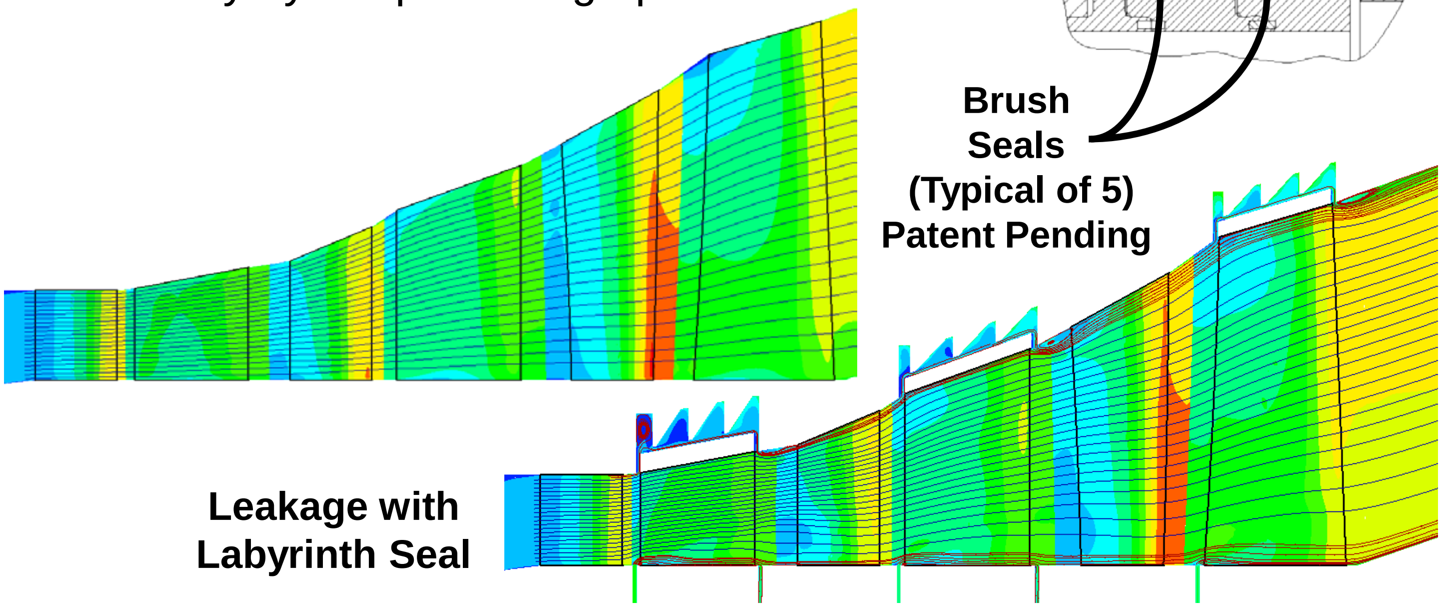
Brush Seals Markedly Improve CN300 Performance

- **Brush seals – patent pending**
  - Used since the early 1980s in aircraft engines
  - Used since the mid-1990s in gas and steam turbines
  - Installed on rotor and stator
  - Significant impact on ORC CN300 performance
    - Reduce gas leakage by 97.8%
    - Improve efficiency by 3.7 percentage points





CN's Combination of Advanced Design Features Lead to a State-of-the-Art Unit

- **Previous ORC system limitations resolved**
  - New CN300 TGU = hermetic, direct-drive, oil-free, magnetic bearings, refrigerant-cooled, no speed governor
- **CN300 design goal: Zero maintenance**
  - Reduced operating/maintenance costs
  - Reduced project lifecycle costs
  - Maximized TGU efficiency
- **CN300 design criteria: Easily customized flow path design**
  - For various heat sources, temperatures, and working fluids
  - To maximize turbine efficiency
  - To maximize client project revenue
- **Now commercially available**

Finished Machined Rotor
(one of three used in the CN300 system)

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