Designing Airfoils for Supercritical CO_2 Turbines: Challenges and Key Considerations

Infinity Turbine LLC

[TEL] +1-608-238-6001 (Chicago

[Email] greg@infinityturbine.com

https://infinityturbine.com/designing-airfoils-for-sco2-turbines-by-infinity-turbine.html

Learn how to design turbine airfoils for supercritical CO_2 systems. Explore aerodynamic, structural, and thermal challenges, material constraints, and how CO_2s high density and real-gas behavior affect turbine design.

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Introduction

Supercritical CO_2 (sCO_2) turbine technology is redefining compact power generation by operating at high pressure and temperature in the supercritical state—where CO_2 exhibits properties of both a liquid and a gas. In this regime, CO_2s density is much higher than that of air, but its viscosity remains gas-like. These characteristics create unique challenges for airfoil and turbine bucket design, influencing everything from aerodynamic efficiency to cooling and sealing strategies.

Understanding CO_2 in the Supercritical Region
At pressures above 7.38 MPa and temperatures above 31°C, carbon dioxide becomes supercritical. Unlike steam or air, sCO_2 maintains liquid-like density (typically 200–800 kg/m³) while preserving gas-like viscosity (~3×10^{-5} Pa·s).

Key Fluid Properties Affecting Design

High Density: Enables high power density and smaller turbomachinery footprints.
Low Speed of Sound: Leads to higher Mach numbers at lower flow velocities, increasing the risk of choking and shock losses.
Real-Gas Effects: Thermophysical properties (specific heat, compressibility, and speed of sound) vary sharply with temperature and pressure, demanding real-gas equations of state during design.

Aerodynamic Considerations

1. Compact Geometry and High Loading
The high density of sCO_2 results in very small volumetric flow rates. Turbine passages are compact, and blade spans are short, leading to high hub-to-tip ratios and strong endwall interactions. Airfoil loading must be carefully balanced to avoid flow separation or excessive diffusion.
2. Real-Gas Aerodynamics
Traditional gas-turbine design correlations (based on ideal gases) fail for sCO_2. Designers must use real-gas property tables (e.g., REFPROP or Span-Wagner equations) to calculate local Mach numbers and thermodynamic states accurately. The lower speed of sound also causes early choking, which must be mitigated through optimized throat areas and controlled expansion angles.
3. Reynolds Number and Loss Mechanisms
Despite small flow paths, the high density yields extremely high Reynolds numbers ($>10^6$), making profile losses low but secondary and tip-clearance losses dominant. Minimizing leakage, endwall vortices, and corner separations becomes more critical than refining the blade's mid-span shape.
4. Stage Efficiency and Shock Control
To prevent transonic losses, stator and rotor exit Mach numbers are typically limited to 0.6–0.9. Real-gas compressibility means that small geometric deviations can lead to local shocks. Therefore, blade camber and diffusion factors must remain moderate ($D \leq 0.6$–0.7).

Structural and Mechanical Design Constraints
1. Blade Stress and Materials
Because of the compact geometry and high rotational speed, centrifugal stresses dominate. Blades are short, but disks and roots endure very high stresses. High-temperature materials such as Inconel 625, Inconel 718, or Alloy 740H are typically used above 550°C.
2. Tip Clearance and Sealing
Small blade spans amplify the effect of tip-clearance losses. Techniques such as abradable seals, brush seals, or squealer tips are employed to reduce leakage. For high-pressure containment, sealing systems must tolerate dense CO_2 without significant leakage or wear.
3. Corrosion and Compatibility
Supercritical CO_2 can cause oxidation, carburization, or corrosion depending on impurities. Stable chromium oxide (Cr_2O_3) surface films are necessary, and alloy selection or surface coatings must consider long-term exposure stability.