Scaling Guidelines for Converting Micro Turbines from Air to Supercritical CO2

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Learn how to adapt micro turbine blades originally designed for air to operate with supercritical CO2. Guidelines cover density differences, scaling rules, torque, flow, and efficiency impacts.

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Using a Radial Outflow Turbine versus a Radial Turbine

A radial outflow turbine can make the gas path geometry more workable for supercritical CO_2 micro-turbines, but you pay for that with higher rotor stresses, more challenging aerodynamics, and usually a lower peak efficiency than the best axial or radial-inflow designs. It is a useful knob when your passages get tiny with sCO_2, but it is not a free win.

Here is how to think about it.

Why sCO_2 makes blades hard to size

At 300 C and high pressure, sCO_2 density can be 100 to 200 kilograms per cubic meter or more. For a given mass flow, the required flow area equals mass flow divided by density times velocity. That makes inlet throats very small in micro hardware. In axial or radial-inflow stages you can run into unmanufacturable slots and excessive tip-clearance fractions.

What a radial outflow stage changes

Radial outflow moves the working fluid from small radius to large radius across the rotor. As the gas expands, its density drops and its volumetric flow rises. Outflow architecture naturally provides more annulus area because area scales with 2 pi times radius times blade height. Growing radius means you can grow area without making the blade height extreme. That directly helps with sCO_2 where you need more area downstream.

Rule of thumb in text form:

Required flow area A equals 2 times pi times radius r times blade height b.
As r increases across the rotor, A can increase even if b is kept moderate.
That can keep minimum throats and tip gaps in a machinable range.

Specific pros for micro sCO_2

1. Manufacturable passages
Outflow lets you start at a small radius where the dense sCO_2 needs very little area and finish at a larger radius where the expanded flow needs more area. This reduces the need for ultra-tall blades or hairline throats.

2. Lower relative Mach at the inlet for a given speed
You can pick a modest inlet radius and shaft speed so that blade tip speed is reasonable where the speed of sound in sCO_2 is lower than air.

3. Strong torque capability
Torque is roughly mass flow times change in angular momentum. Larger exit radius raises torque leverage, which is helpful at micro scale.

The trade-offs you must accept

1. Rotor stress rises fast
Centrifugal stress scales with radius squared times speed squared. Because the exit radius is larger, for the same rpm the rim stress at the outlet can be high. You will likely need to reduce rpm or thicken the rim and choose a stronger alloy.

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The use of supercritical CO2 (sCO2) as a working fluid in turbines is expanding rapidly due to its compact power density and efficiency potential. However, turbine stages originally designed for air cannot be directly used with CO2. The large difference in density and thermophysical properties requires careful re-scaling. Below is a guideline for adapting a micro turbine blade designed for air into one suitable for CO2 service.

Step 1. Establish the CO2 Design Point

Define the inlet total temperature, inlet total pressure, target pressure ratio, and desired mass flow. For CO2 at 300 degrees Celsius and 200 bar, the density is about 170 kilograms per cubic meter. By comparison, air at 300 degrees Celsius and 1 bar has a density of about 0.6 kilograms per cubic meter. This means CO2 is nearly 300 times denser than hot air.

Step 2. Preserve Similarity Parameters

To maintain aerodynamic similarity, you must hold the following non-dimensional values close to the air design:

Flow coefficient = axial velocity divided by blade speed
Stage loading = enthalpy drop per stage divided by blade speed squared
Relative exit Mach number = relative velocity at rotor exit divided by speed of sound
Solidity = blade chord divided by spacing

These parameters govern turning angles, losses, and efficiency.

Step 3. Flow Area and Speed Scaling

Mass flow equals density times area times axial velocity. For a given blade speed and flow coefficient, the required area scales inversely with density.

Example:
For air at 300 C, density = 0.6 kg per cubic meter. For CO2 at 200 bar, density = 170 kg per cubic meter.

If an air turbine needed an annulus area of 0.0011 square meters to pass 0.1 kg per second, then with CO2 at the same conditions, the area would be about 0.000004 square meters for the same mass flow. This is impractically small, so in practice you must reduce mass flow, reduce blade speed, or increase flow coefficient.

Step 4. Torque and Shaft Loading

Stage work equals stage loading multiplied by blade speed squared. Power equals mass flow times stage work.

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