AAE 538: Air-Breathing Propulsion

Lecture 16: Turbines

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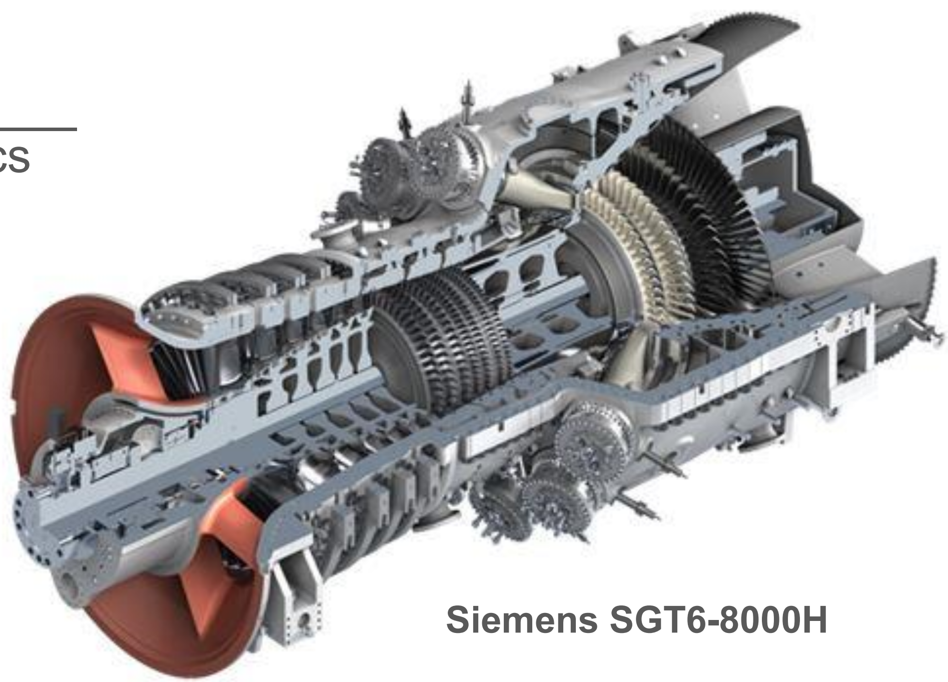
Introduction

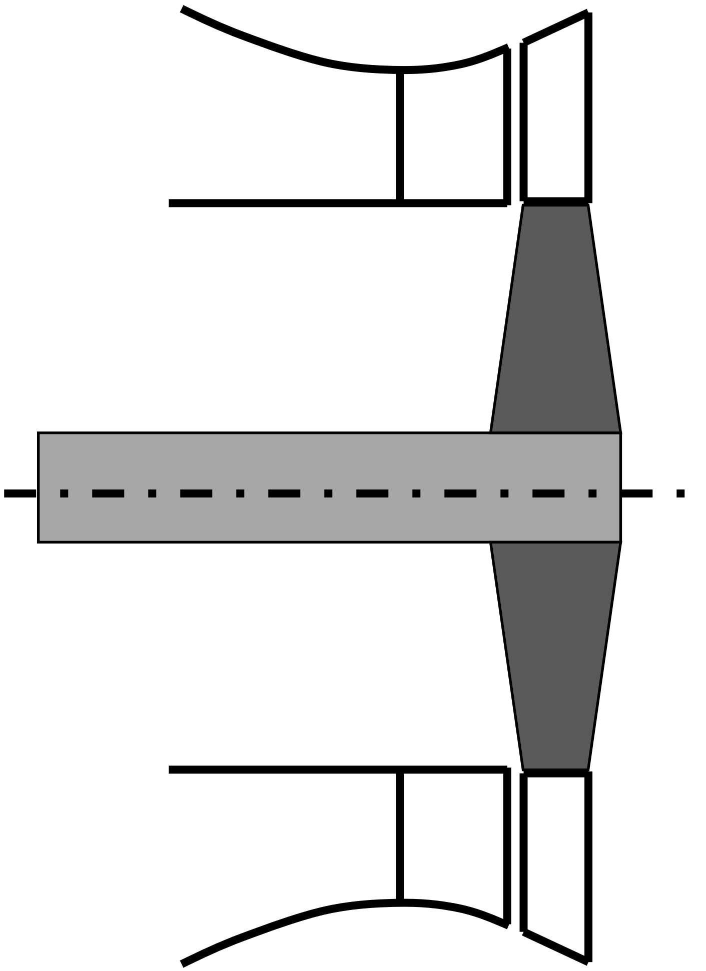
Turbine Design

- In the case of the axial compressor, we saw that the design was driven by the behavior of the ________________________ operating with adverse pressure gradients.
- In the case of the turbine, we now have a favorable pressure gradient so that this restriction is of no concern.
  - Stages can operate with much _______________ pressure changes in the turbine than in the compressor
- Blade load limitations are imposed by _______________ and ___________________ considerations, instead of fluid mechanics
  - Extremely high component temperatures limit the mechanical load capability as the material strength decays.



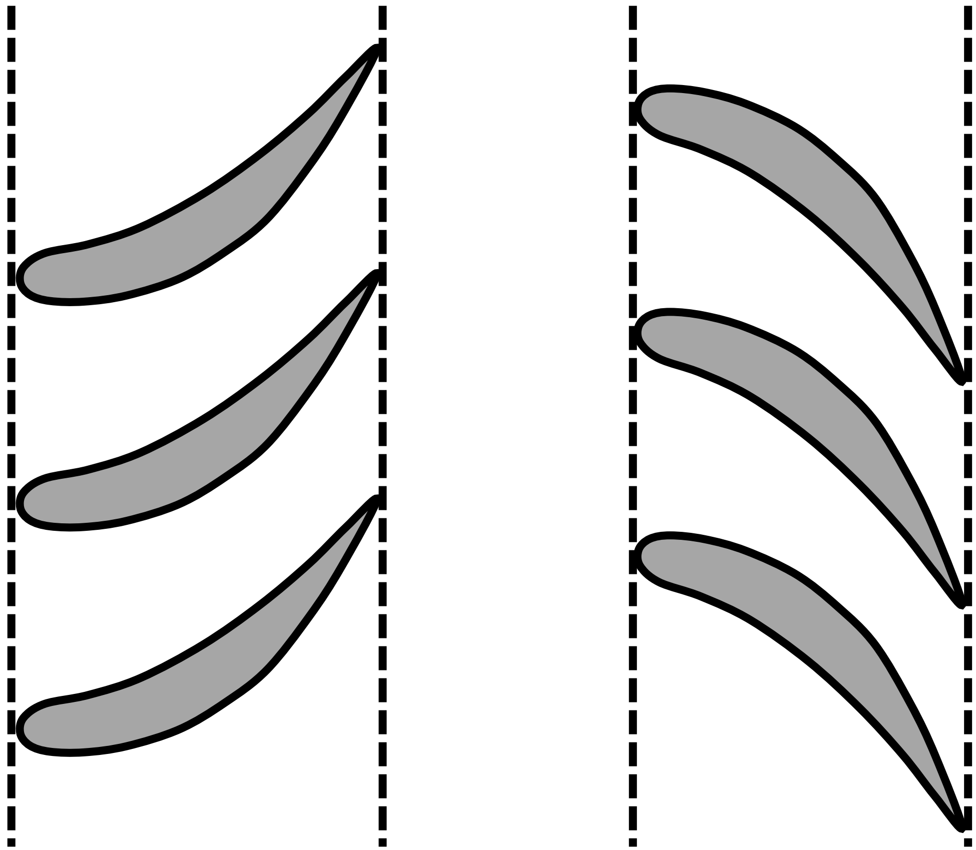
Siemens SGT6-8000H

Axial Turbines



- In the case of the turbine, the fluid is ______________________________.
  - For this reason, it is more useful to consider the stationary row of vanes (often referred to as the nozzle) upstream of the rotor stage.

Axial Turbines



- Note that, here, the change in tangential velocity is ____________________ to the direction of the blade rotation.

Axial Turbines

- Applying the angular momentum relationship to this situation, we see that the power generated by the turbine is:

  therefore, just as with the compressor, changes in the tangential velocity determine the power (or work) output of the turbine stage. Note the sign difference from the compressor work

- The work per unit mass is simply the power divided by the mass flow rate. We can also express the work as the change in ______________________ across the stage by considering the energy equation. Therefore, we can write:

- Assuming the flow is adiabatic, we note that there is no ______________________ loss across the nozzles. We can then write the stagnation temperature drop as:

Axial Turbines

- Plugging back into the energy balance gives:

  Which indicates that the work output is a function of the amount of flow turning which takes place in through the turbine rotor passages.

- The degree of reaction definition is different for a turbine, compared to our previous derivation for an axial compressor, due to the direction of energy transfer.
  - For a turbine, the degree of reaction is defined

$$R = \frac{h_2 - h_3}{h_1 - h_3} = \frac{\Delta h_{rotor}}{\Delta h_{stator}}$$

Axial Turbines

- Writing the energy equation relative to the moving rotor gives:

- While the energy equation across the stage gives

- Combining the definition of R and the energy equation for the stage, we find

- For the compressor, boundary layer behavior dictated the we operate near $R = 0.5$, but this restriction does not exist in the turbine.
  - For instance, it is perfectly acceptable to have the entire enthalpy drop in the nozzle. Turbines of this type are called _________________________ turbines.
  - If only a fraction of the enthalpy drop occurs in the nozzle (with the remainder in the rotor), then the device is called a _________________________ turbine.

Impulse Turbines

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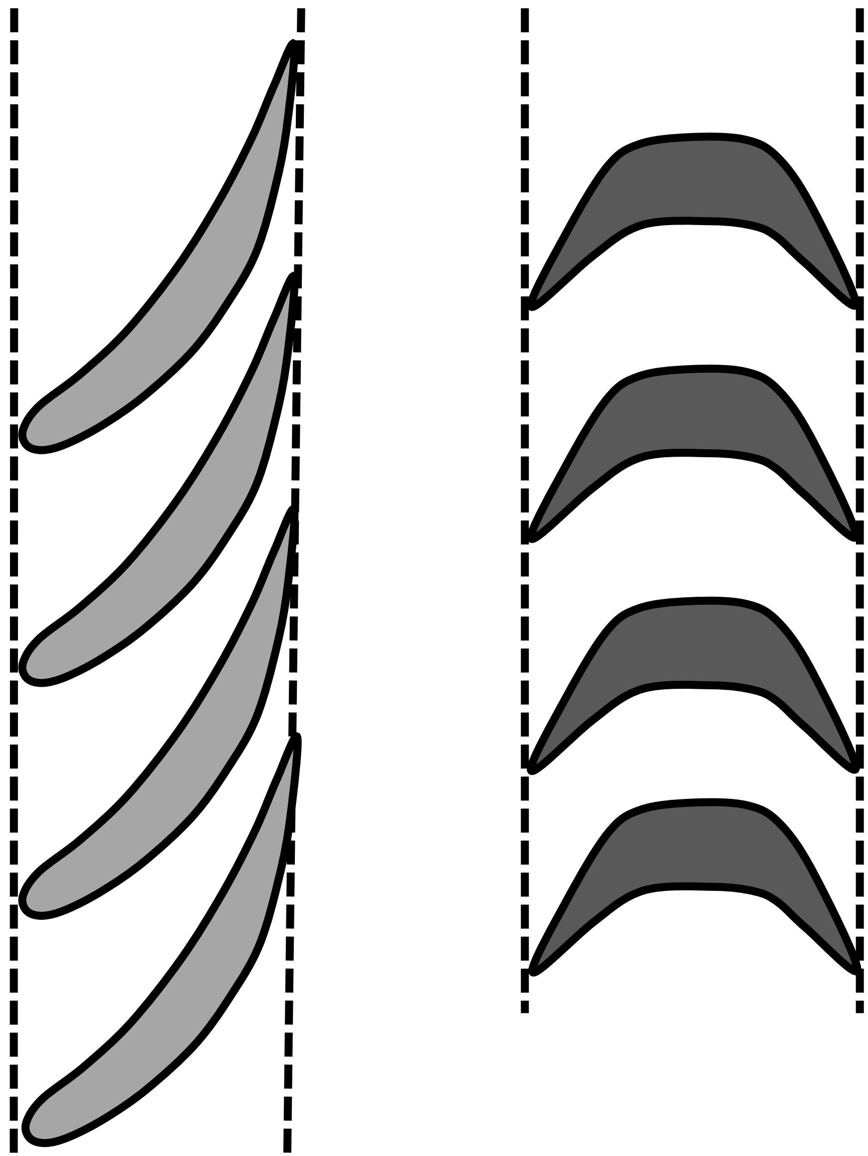

Impulse Turbines

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- Since, by definition, there is ______________________ across the rotor, the energy equation gives

  which implies that . Employing our constraint of axial velocity, we may write:

- Next, we need to express the change in tangential velocity in terms of blade angles. While there are numerous ways to accomplish this, let us express our result in terms of the nozzle exit angle, α_2. To do so, we start with

  since from our above. Substituting for $w_{\theta,2}$ gives

Impulse Turbines

- Substituting in from our work output equation, we obtain

- Evidently ________________________ to achieve a high work output.
  -
  -
  - A typical design value around $70°$ tends to minimize losses.
- Another factor which can reduce performance of the impulse turbine design is _____________ remaining in the exhaust.
  - Since the turbine exhaust is converted to axial velocity, and hence thrust, it is desirable to have no swirl in the flow leaving the last stage of the turbine.
    - Swirling components of velocity don't contribute to thrust.

Impulse Turbines

- This requirement can be express as , which implies
- For this special situation, we can show that the work output becomes
- Therefore the performance of a single-stage impulse turbine can be obtained for a given inlet stagnation temperature if the rotational speed at the mean blade radius, U, is known.
  - Conversely, one could use $c_{\theta,2} = 2U$ to determine the turbine diameter for a given shaft rotational speed in this situation.

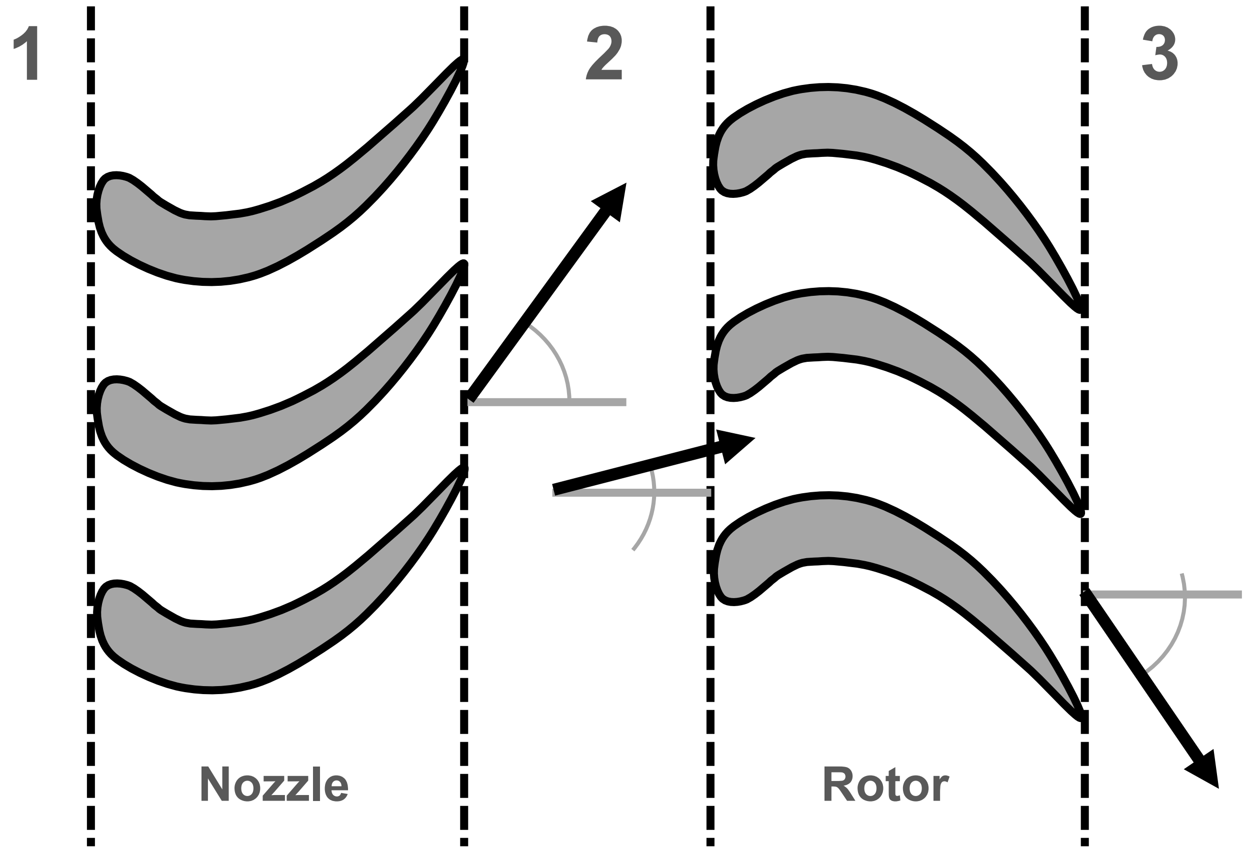
Impulse Turbines

- Turbines with large work requirements cannot typically use a simple impulse stage.
    -
    -
- Multi-stage systems and reaction turbines typically employed in ABP applications

GE Energy Rankine Cycle Turbine

The 50% Reaction Turbine

- There is no unique desire to have a 50% reaction stage for a turbine, but we can use this design as an instructive example to shed some light on the behavior of these devices.



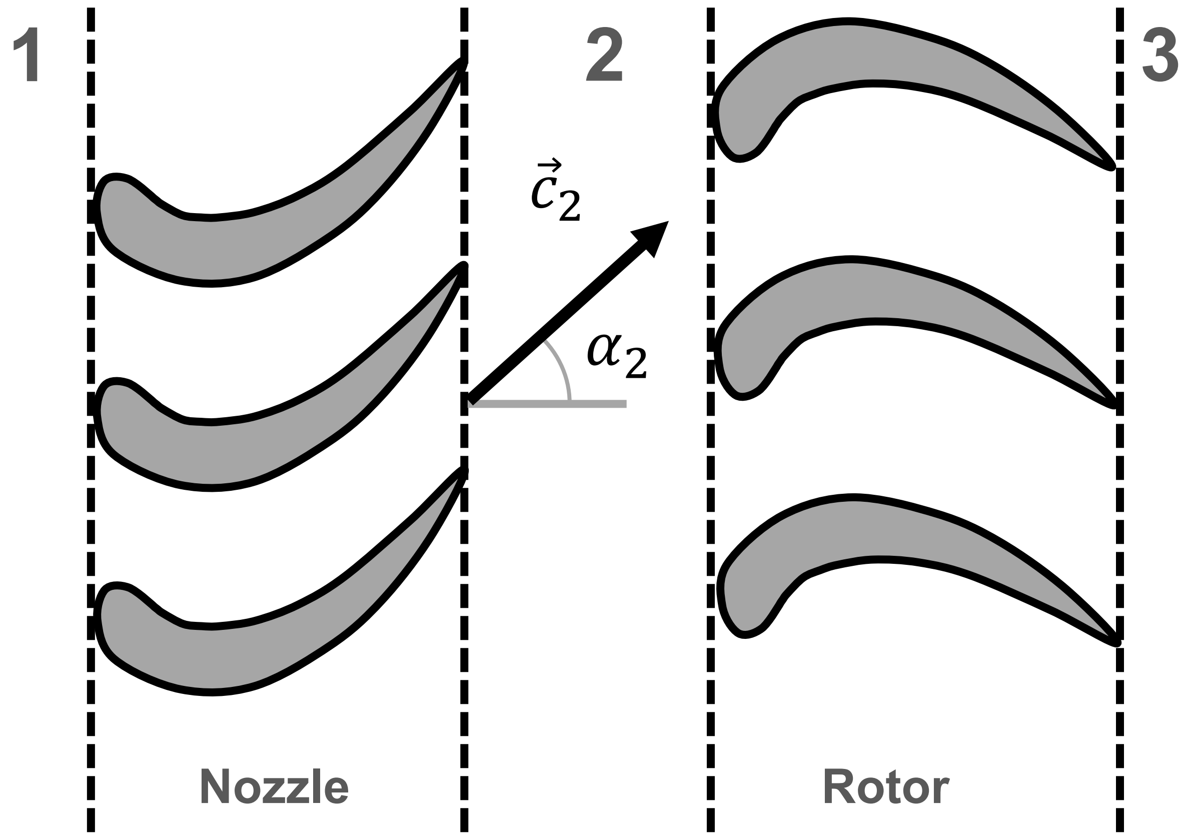
Velocity triangles and blading arrangements for the 50% reaction turbine stage with constant axial velocity.

The 50% Reaction Turbine

- Note that the velocity triangles are ____________________ for this unique case.
  - This symmetry, combined with the assumption of _______________________, permits us to write:
- Using this result, and noting that ________________ gives the following stagnation temperature drop for the stage:
- As in the case of the impulse stage, we note the desirability for high _____ for high work output.
  -
  -

The 50% Reaction Turbine

- Consider the special case where we desire a completely axial velocity at the exit of the rotor (no swirl)
  -
  -



The 50% Reaction Turbine

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- In this unique case, we see that the stage stagnation temperature drop is:

Which is ______________ the value we obtained for the impulse turbine.

  - Therefore, the impulse stage can provide _____________ than a 50% reaction stage turbine provided the turbine blades can withstand the imposed stresses.
  - However, the high degree of turning required for the impulse stage will lead to ___________________________________ for a given U and work requirement.

- As we might expect, there will be some cases where a reaction turbine is preferred over an impulse design, and vice-versa.
  - The turbine can be designed for ________________________ (greater than zero) depending on the specific requirements.
  - 50% may not be optimal, but the trade-offs can be balanced to optimize the design.

Real Turbine Performance

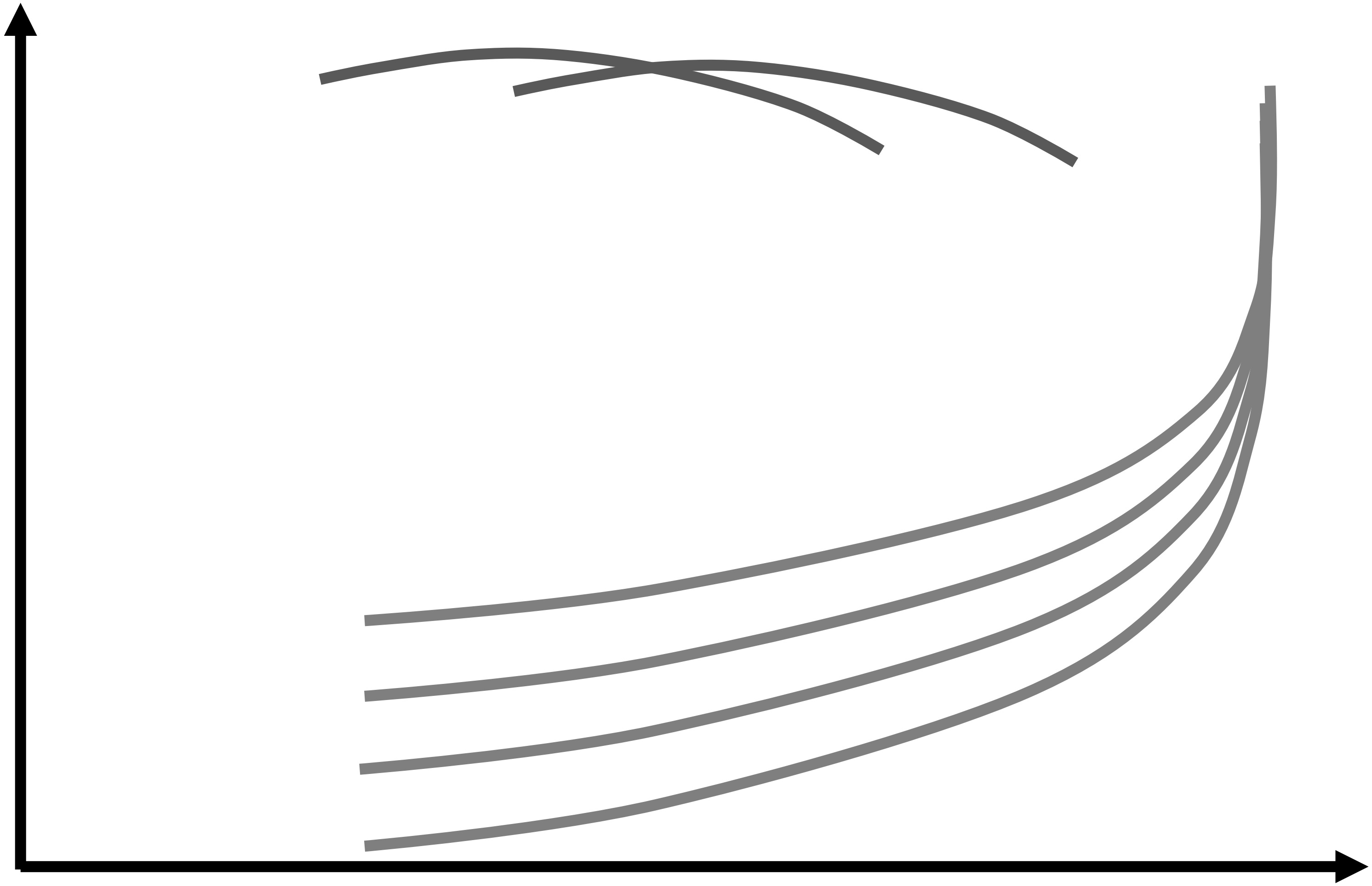
- As in the case of the compressor, we can express the pressure ratio across the turbine as a function of several dimensionless groups.

  - In a similar manner, we can factor out any dependence on D and nondimensionalize _____ and ______ by the sea-level static conditions.
  - The Reynolds number is nearly always high enough to neglect the influence of the ________ term.

- Therefore, as in the compressor, the turbine pressure ratio can be expressed as a function of a _______________ and __________________, such that:

Real Turbine Performance

Turbine Performance Map



Real Turbine Performance

Turbine Performance Map

- Operating limits are set by the ______________________________ for a given speed and inlet temperature.
    - Note that there is no limit analogous to the surge line that appears in the compressor maps.
        -
    - The limit on the right hand side of the curves if the mass flow which chokes the nozzles of the turbine inlet.
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