The Effect of Isentropic Exponent on Supersonic Turbine Wakes

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Whittle Laboratory

Importance of Isentropic Exponent (*k*)

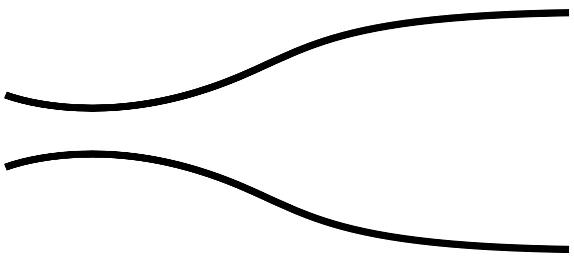
$$k = \frac{\rho}{p}\left(\frac{\partial p}{\partial \rho}\right)_s$$

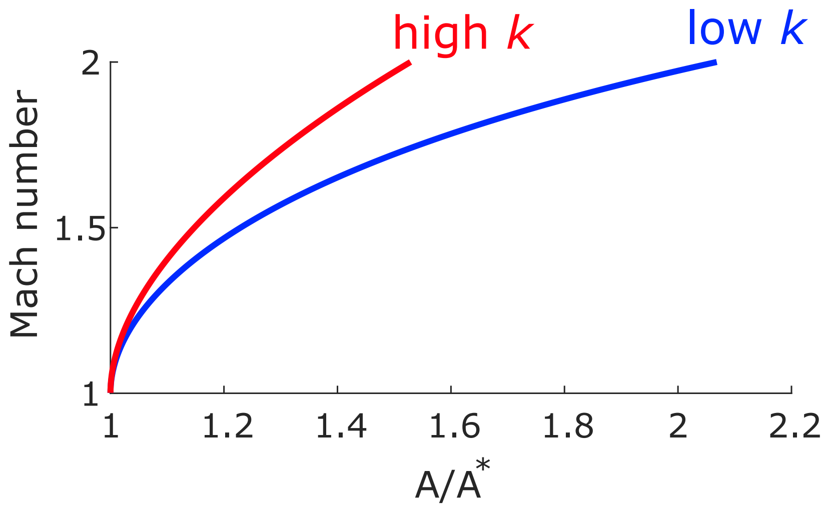
- Based upon the variation of pressure and density across an isentropic expansion
  - For perfect gas $k = c_p/c_v$; $k > 1$
  - For real gas $k \neq c_p/c_v$

Effect of Isentropic Exponent (*k*)

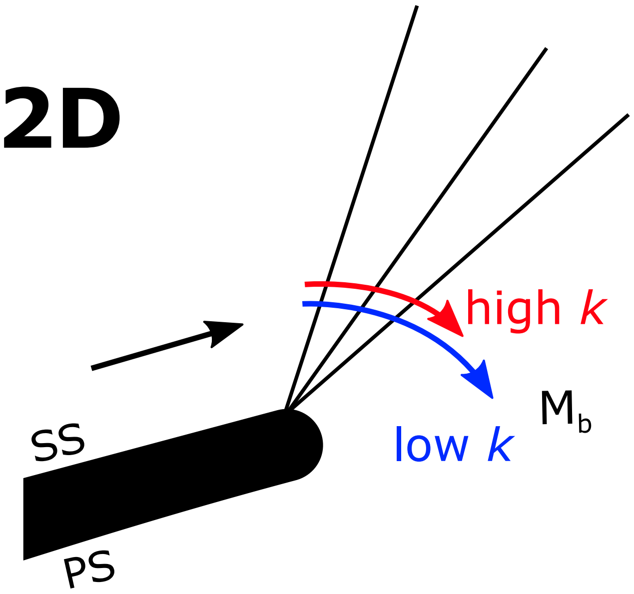
1D

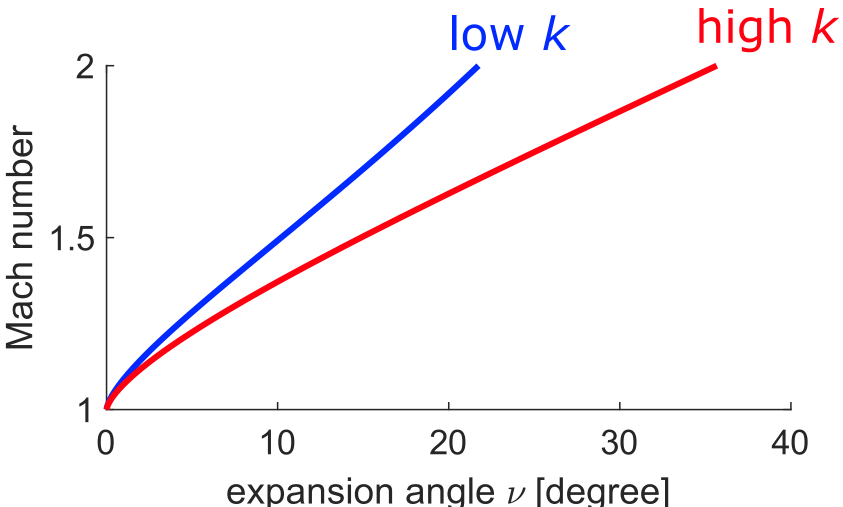
converging-diverging nozzle





2D





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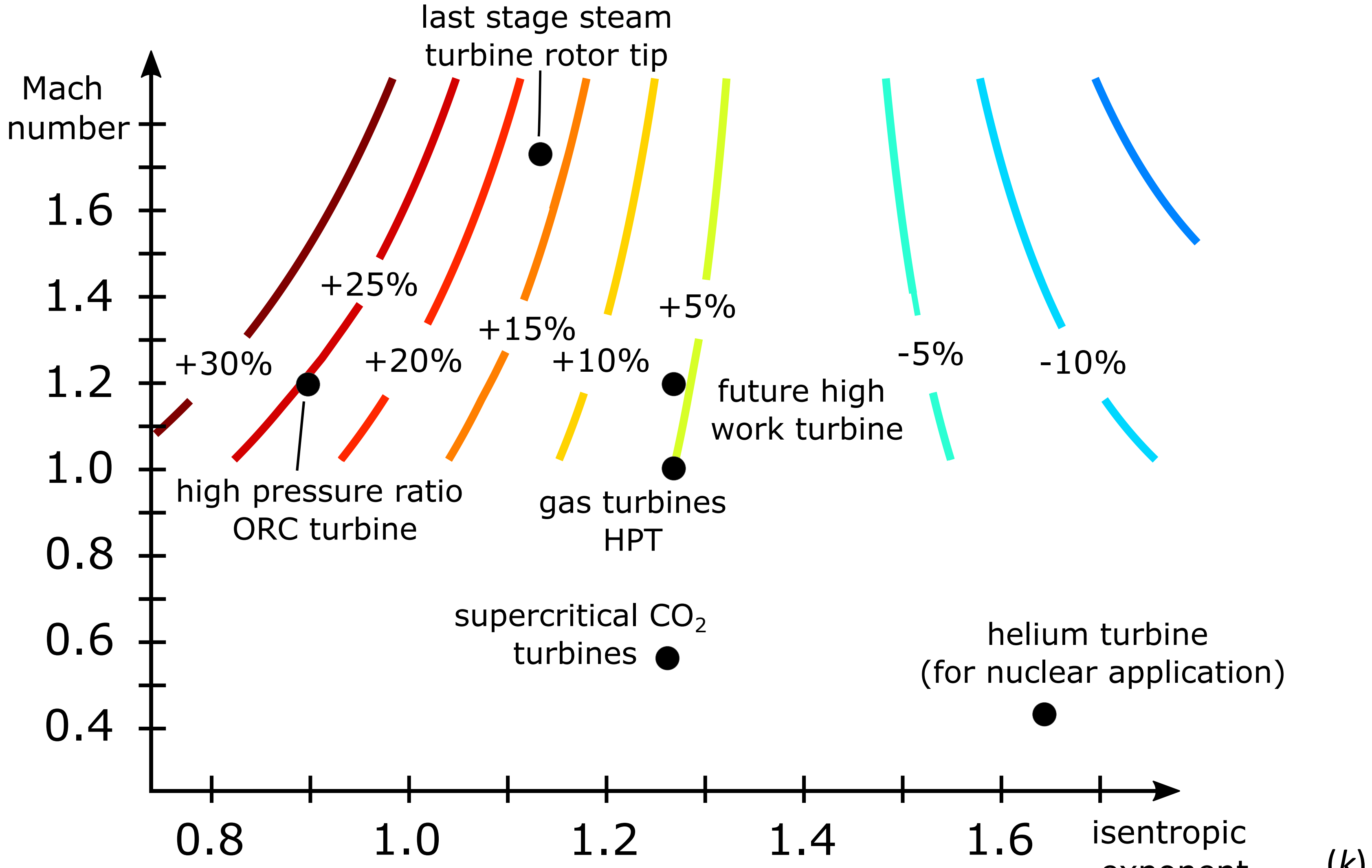
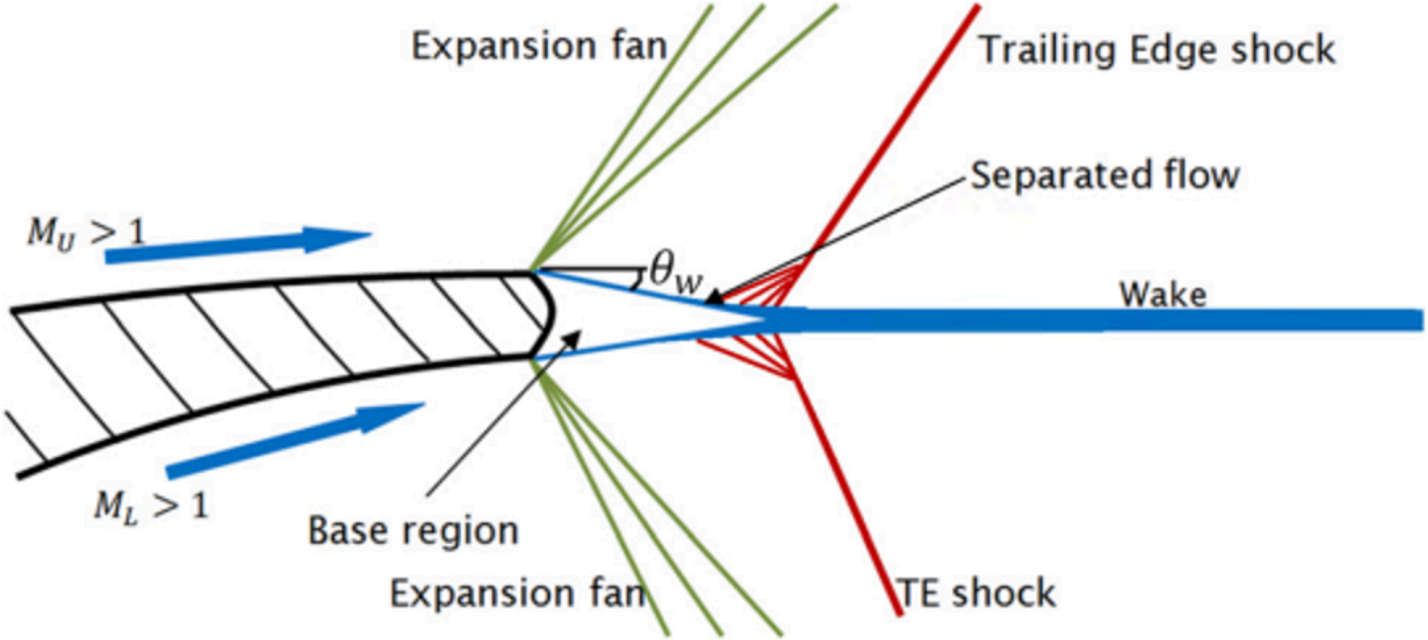


Variation of Turbine Loss relative to air[1]

[1] D. Baumgärtner, et al “The Effect of Isentropic Exponent on Transonic Turbine Performance” 2020

Supersonic Wake Flows

- Large portion of vane loss due to the supersonic flow around the trailing edge

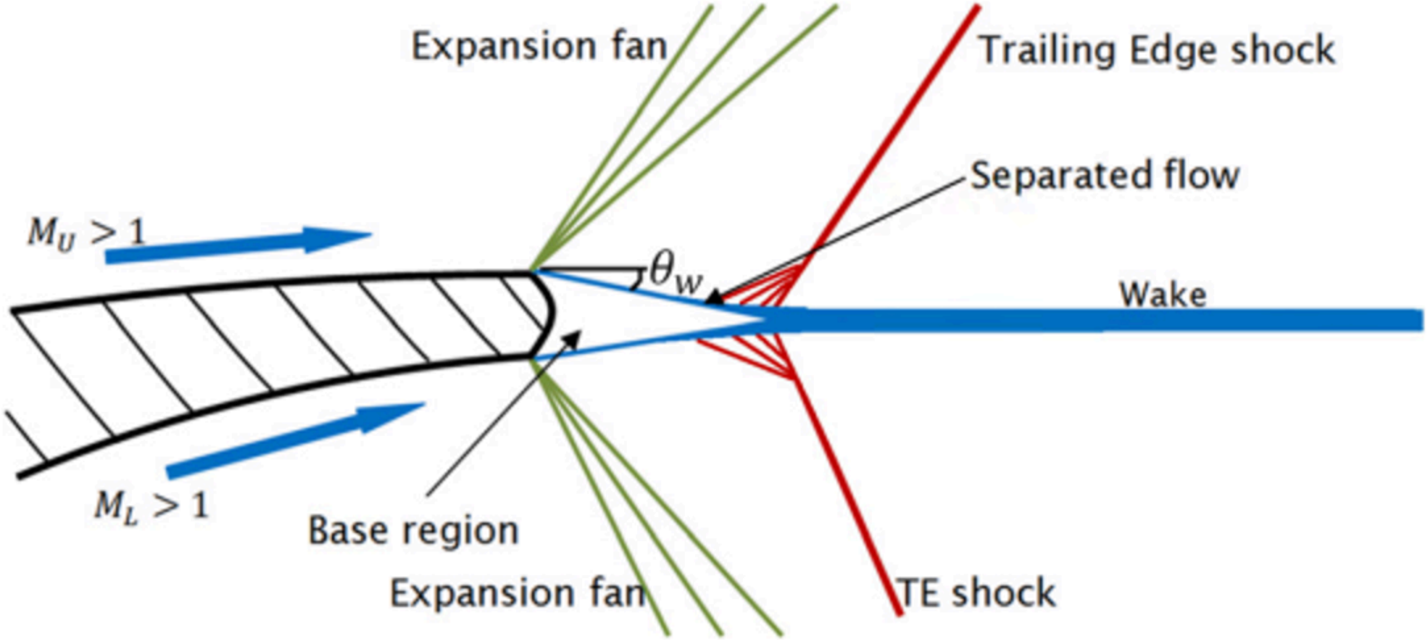


Typical Supersonic Trailing Edge Flow[2]

[2] Durá Galiana, F. J. et al. "A Study of Trailing-Edge Losses in Organic Rankine Cycle Turbines." 2016

Trailing Edge Loss in ORC Vanes

- Large portion of vane loss due to the supersonic flow around the trailing edge
- Currently there is a lack of experimental data for ORC trailing edge flows



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Research Overview

Research Aims

- Provide a detailed experimental data of an ORC wake flow
- Identify how the isentropic exponent affects wake flows

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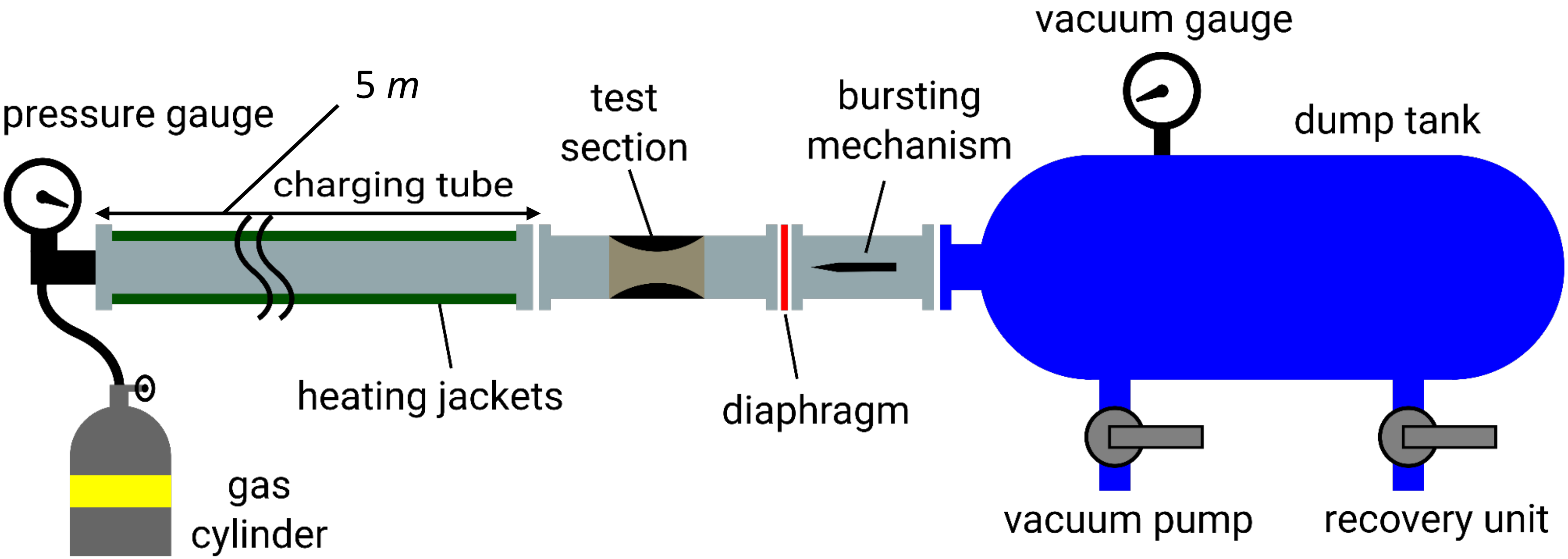
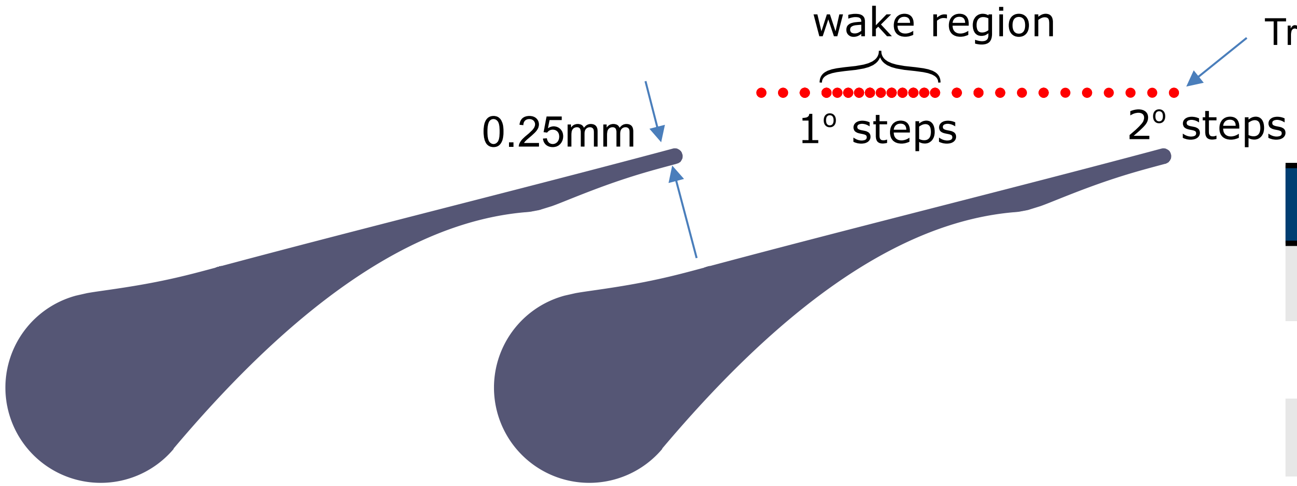
Variable Fluid Test Rig



	p_o [bar]	T_o [K]	Re	k	Γ	Z	PR
air	8.2	293	$1.6\text{x}10^6$	1.40	1.21	1.0	4.75
CO_2	8.2	400	$1.4\text{x}10^6$	1.27	1.11	0.98	4.75
R134a	5.0	293	$1.6\text{x}10^6$	1.07	1.02	0.88	4.75

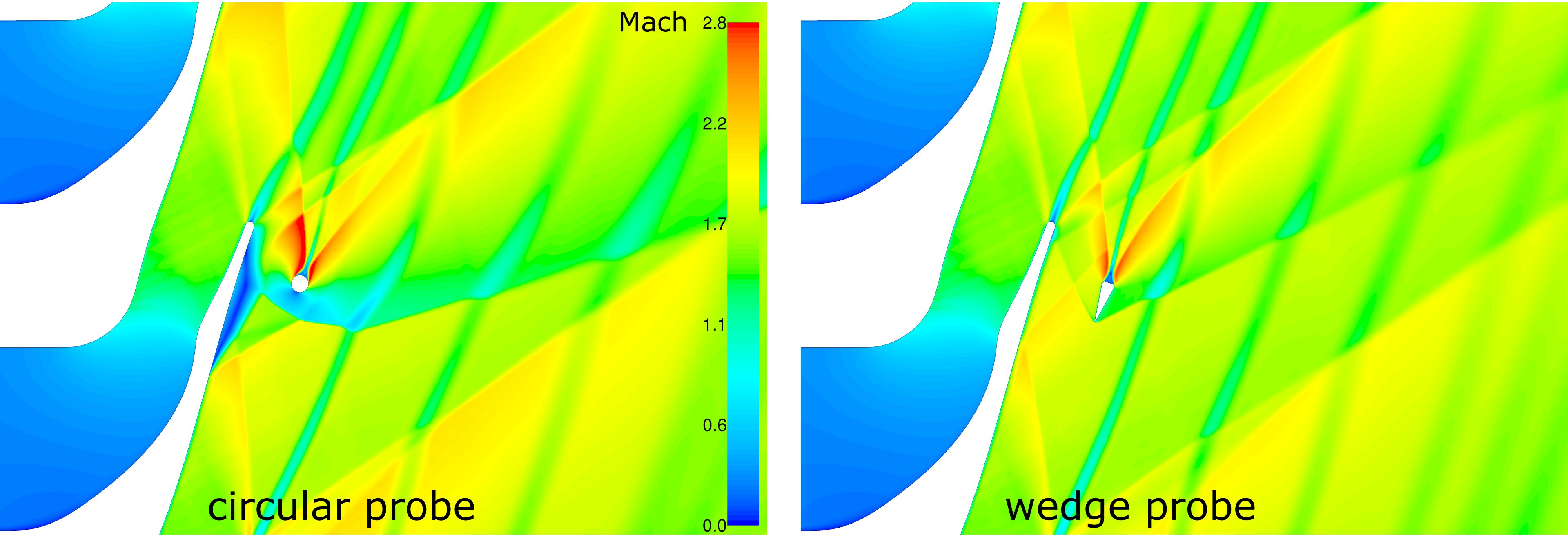
Working Section



Design Parameters	
Mach number	1.45
Isentropic exponent	1.4
Inlet flow angle	0°
Exit flow angle	75°

- Geometry design based on air as a working fluid
- Geometry held constant for each fluid, hence exit Mach number varies
- Wind tunnel has short run times ~100ms: traverse obtained through casing rotation
- Major Challenges:
  - Small scale (TE = 0.25mm) so avoiding blockage is key – bespoke probe design required
  - Repeatable results needed - wake traverse requires separate runs

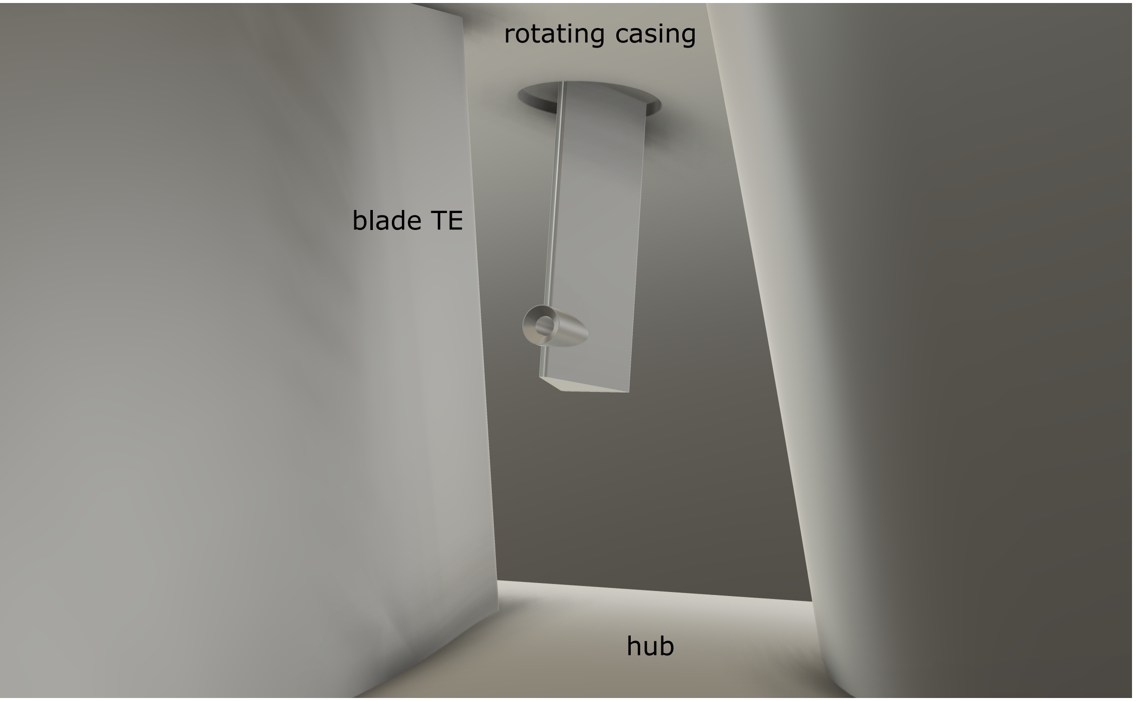
Supersonic Probe Design



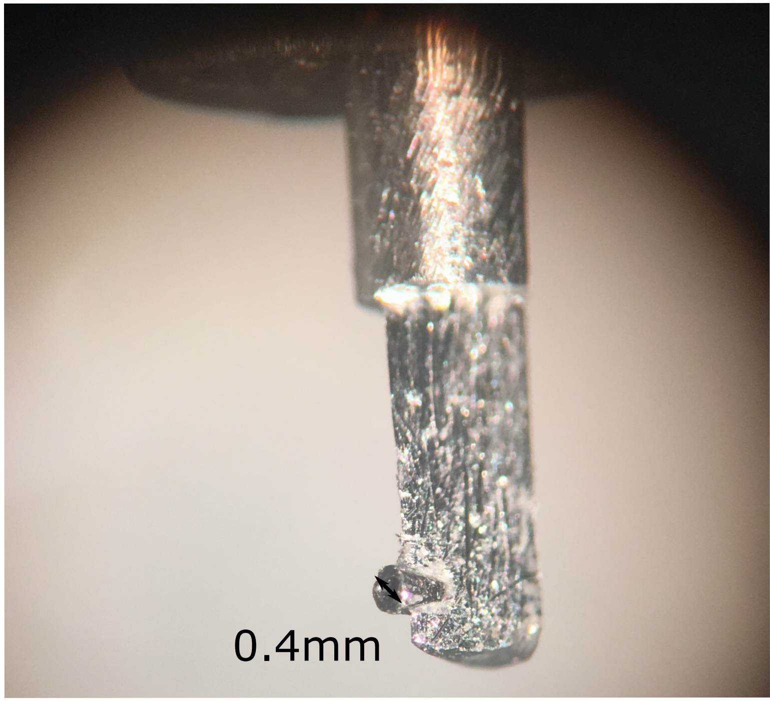
Distribution of Mach number with Probe

- First iteration of probe design was circular
- Relatively large probe required due to mechanical requirements
- Caused large interference with vane
- Wedge supported pitot probe developed

Supersonic Probe Design



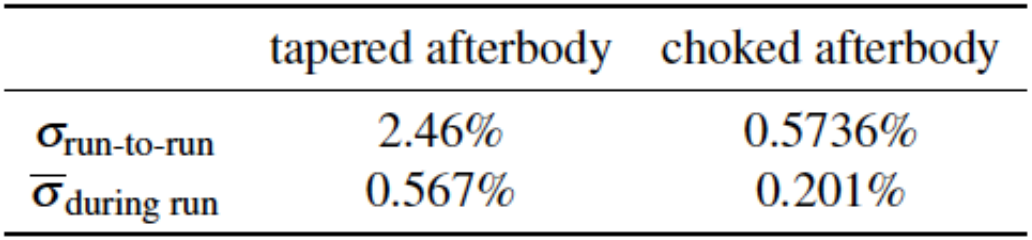
CAD Representation of Probe



Photograph of Probe

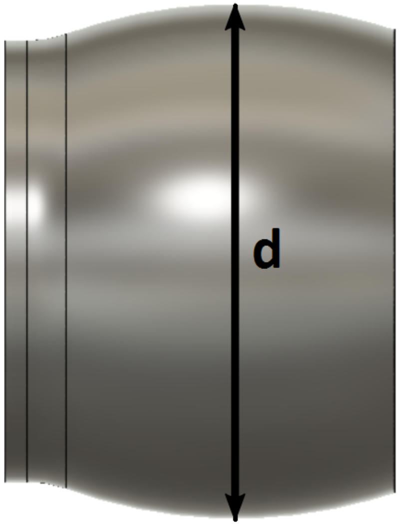
- Probe machined in-house from aluminum
- Stainless steel hypodermic tubing glued into wedge shape
- Positioned at mid-span
- Rotatable around own axis – aligned with freestream flow

Test Section Afterbody



	tapered afterbody	choked afterbody
$\sigma_{\text{run-to-run}}$	2.46%	0.5736%
$\overline{\sigma}_{\text{during run}}$	0.567%	0.201%

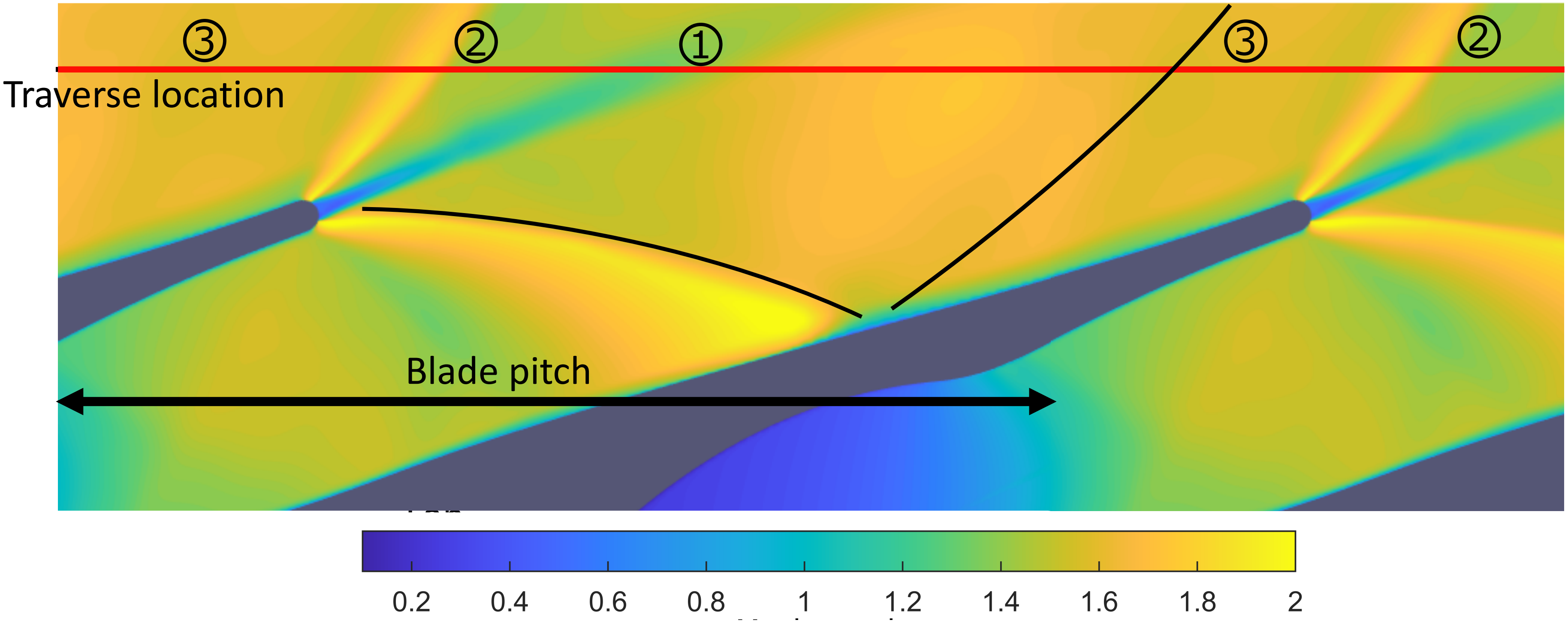
Repeatability of Wall Static Measurements



Afterbody

- Repeatability improved with the introduction of second throat downstream of
- Also gave control of cascade pressure ratio
- Improved run-to-run repeatability
- Reduced noise in quasi-steady flow region

Location of Wake Traverse



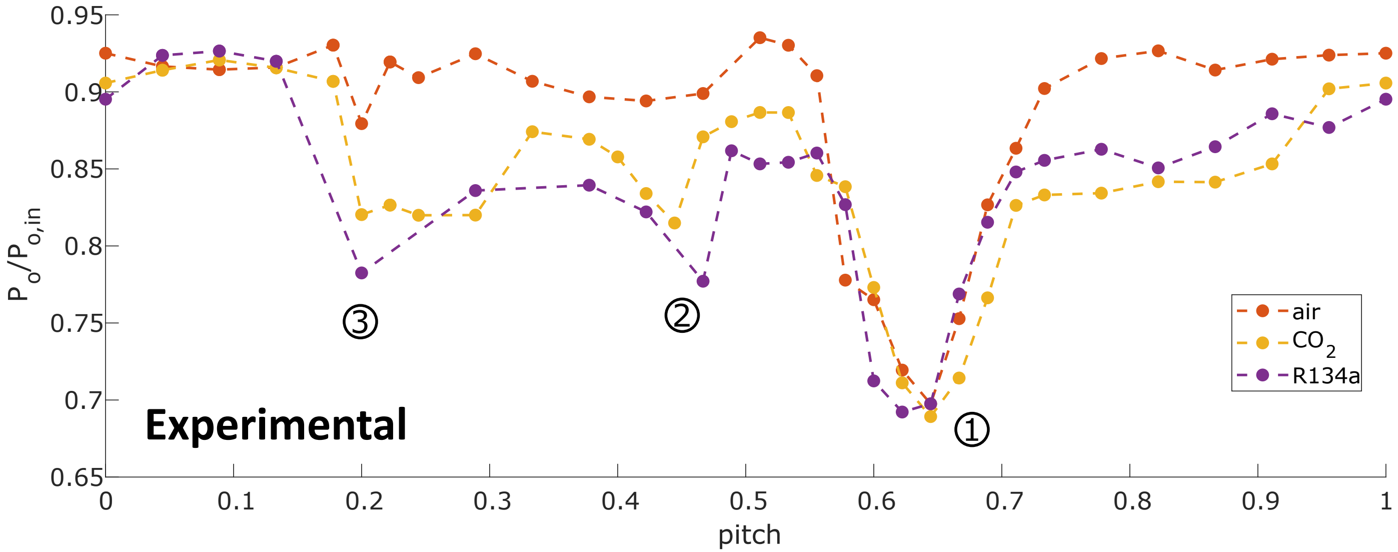
Mach Number Distribution at midspan (CFD)

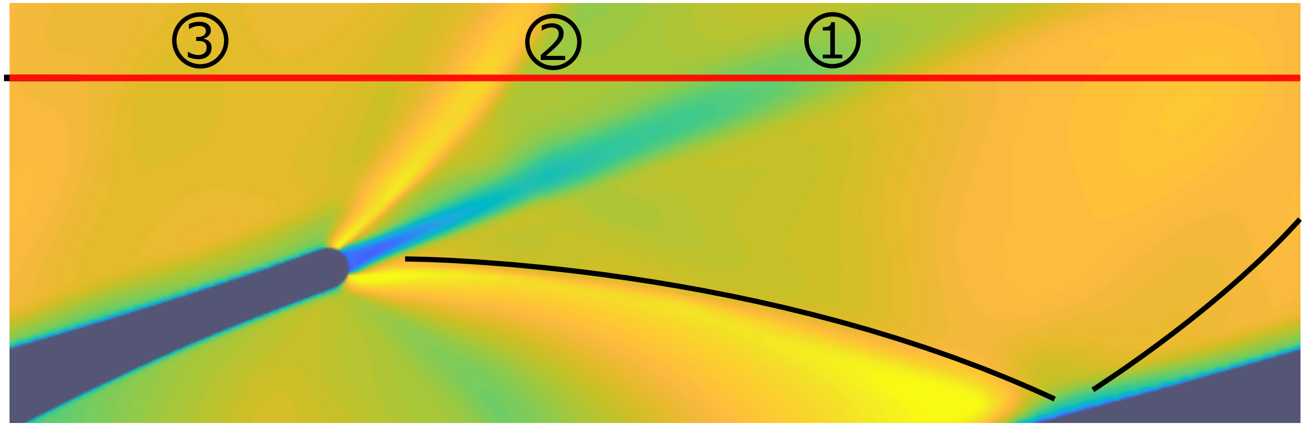
Main flow features:

1. Blade Wake
2. Expansion Fan
3. Reflected shock

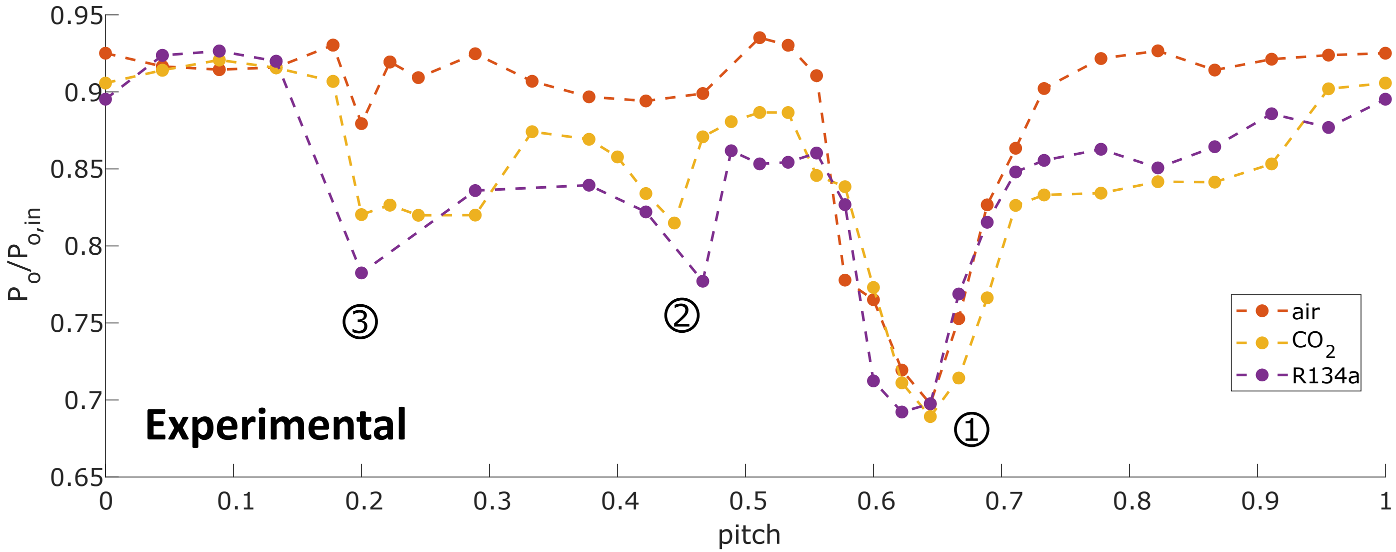
CFD : Rans with ANSYS Fluent, wall functions and SA turbulence model

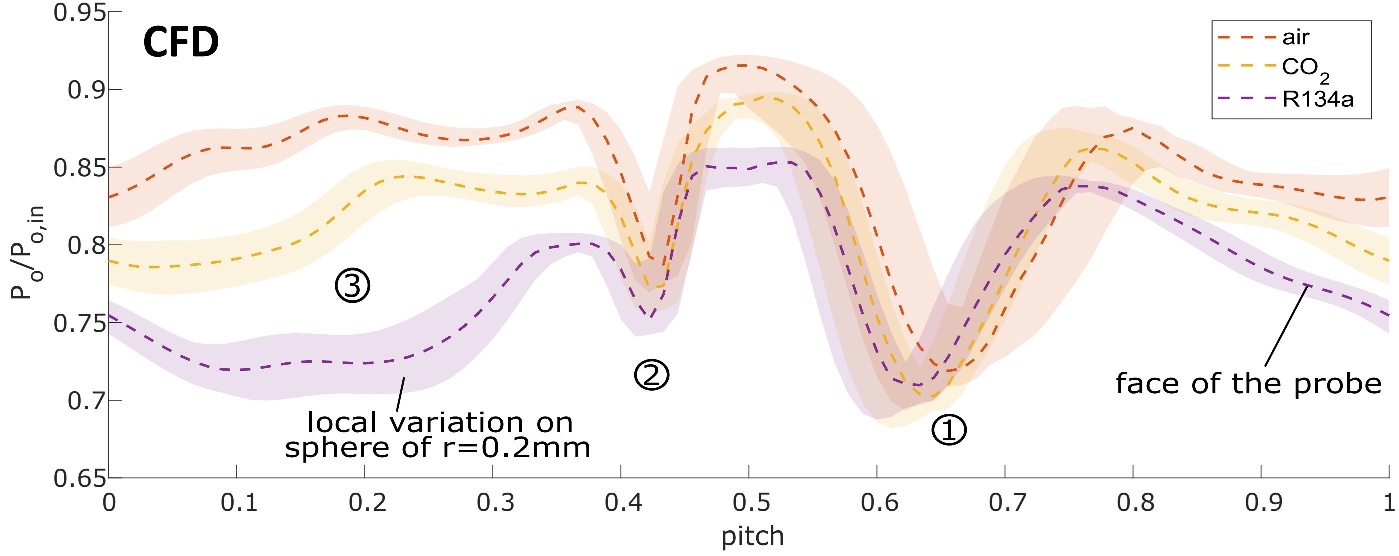
Experimental Wake Measurements





Comparison of Measurements and CFD





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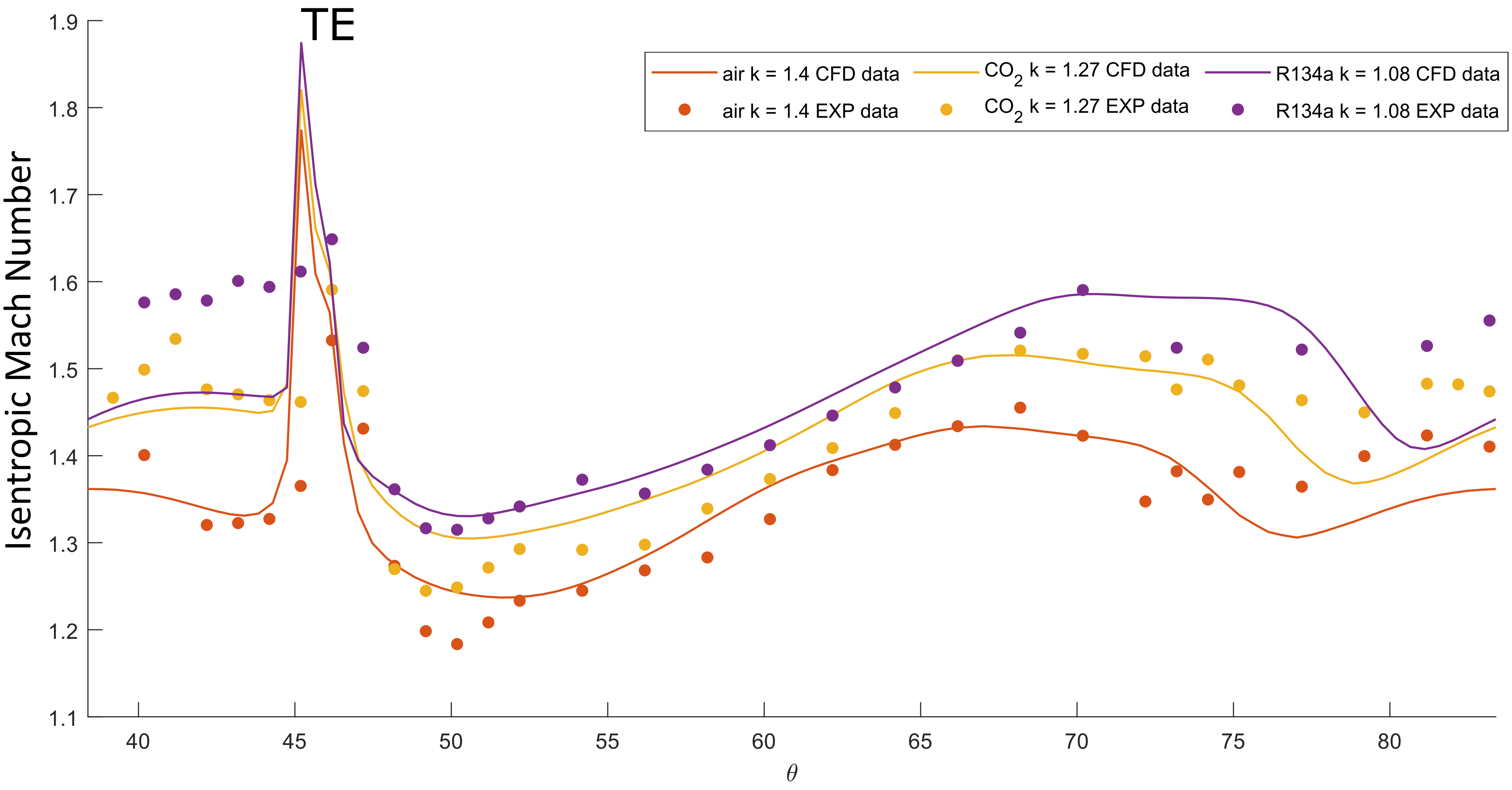

Wall Static Measurements

Research Overview

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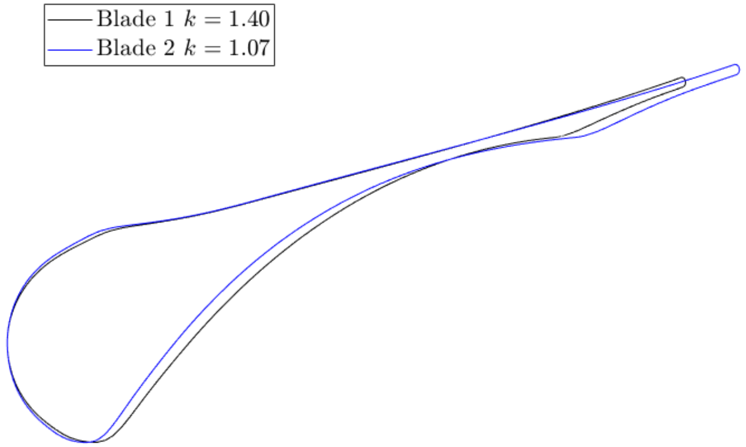
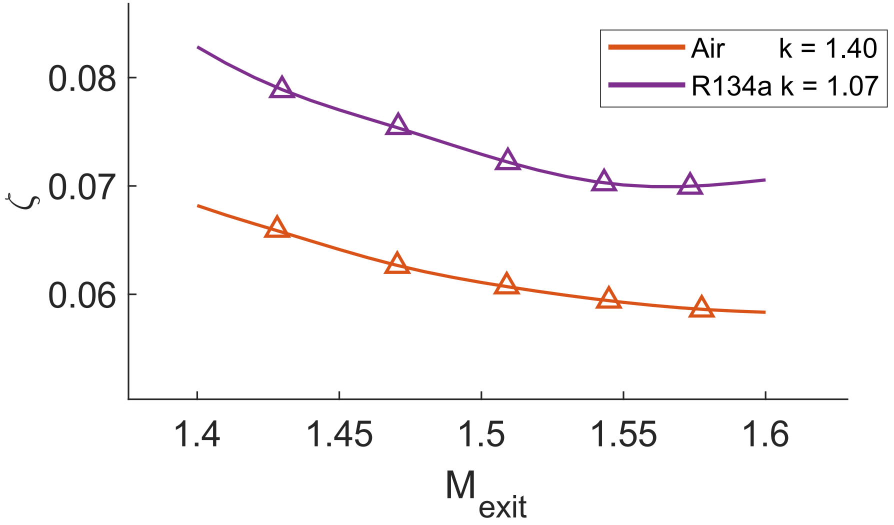
- Provide a detailed experimental data of an ORC wake flow
- **Identify how the isentropic exponent affects wake flows**

Effect on Wake at Constant exit Mach Number

- Experimental data obtained at constant pressure ratio - not constant loading
- 2D CFD used to achieve dynamic similarity
  - Reynolds Number
  - Exit Mach number - hence blade loading
- Mixed-out loss coefficient higher for R134a (low k)

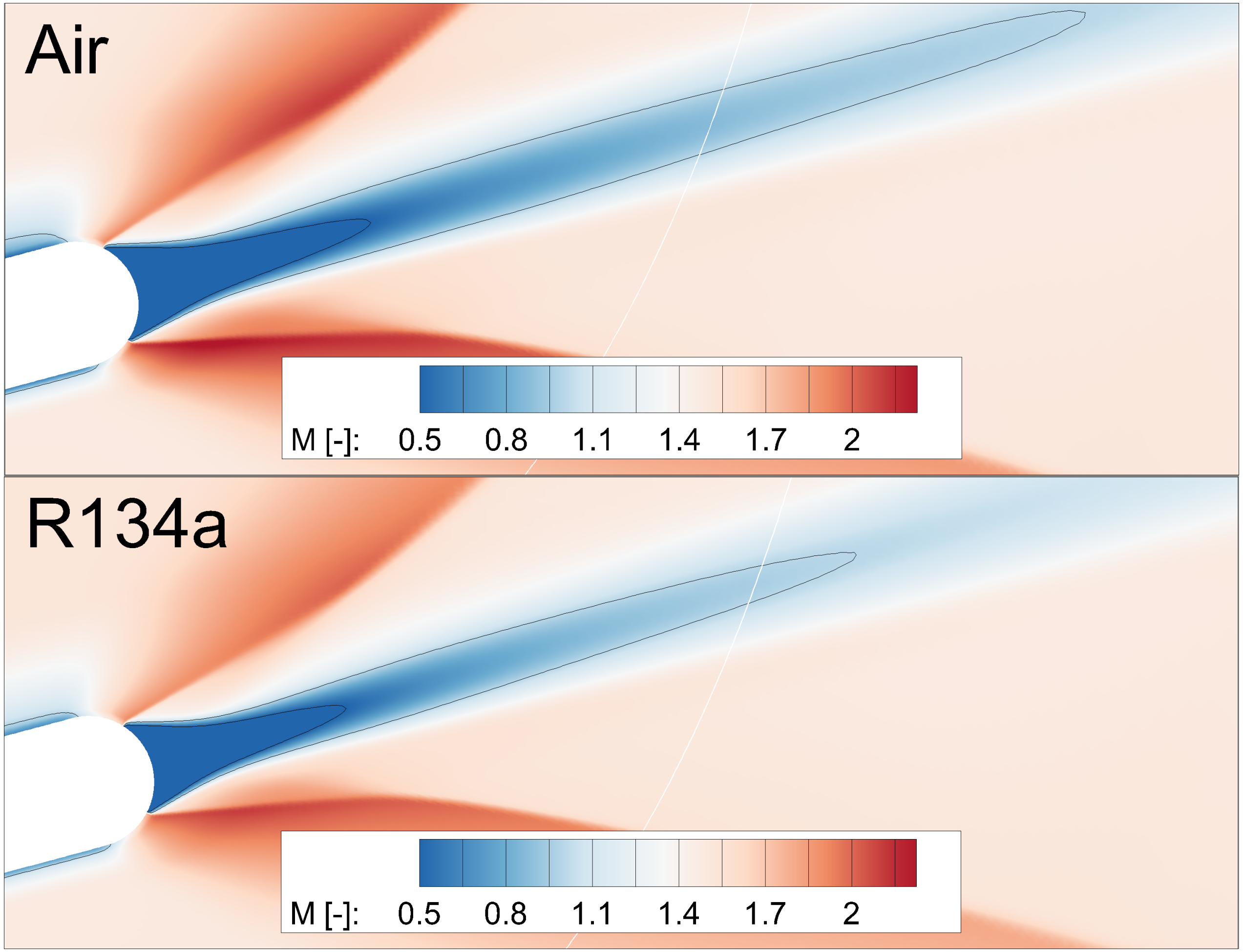




Variation of Loss with exit Mach number

$$\zeta = (H - H_s)/(H_o - H_s)$$

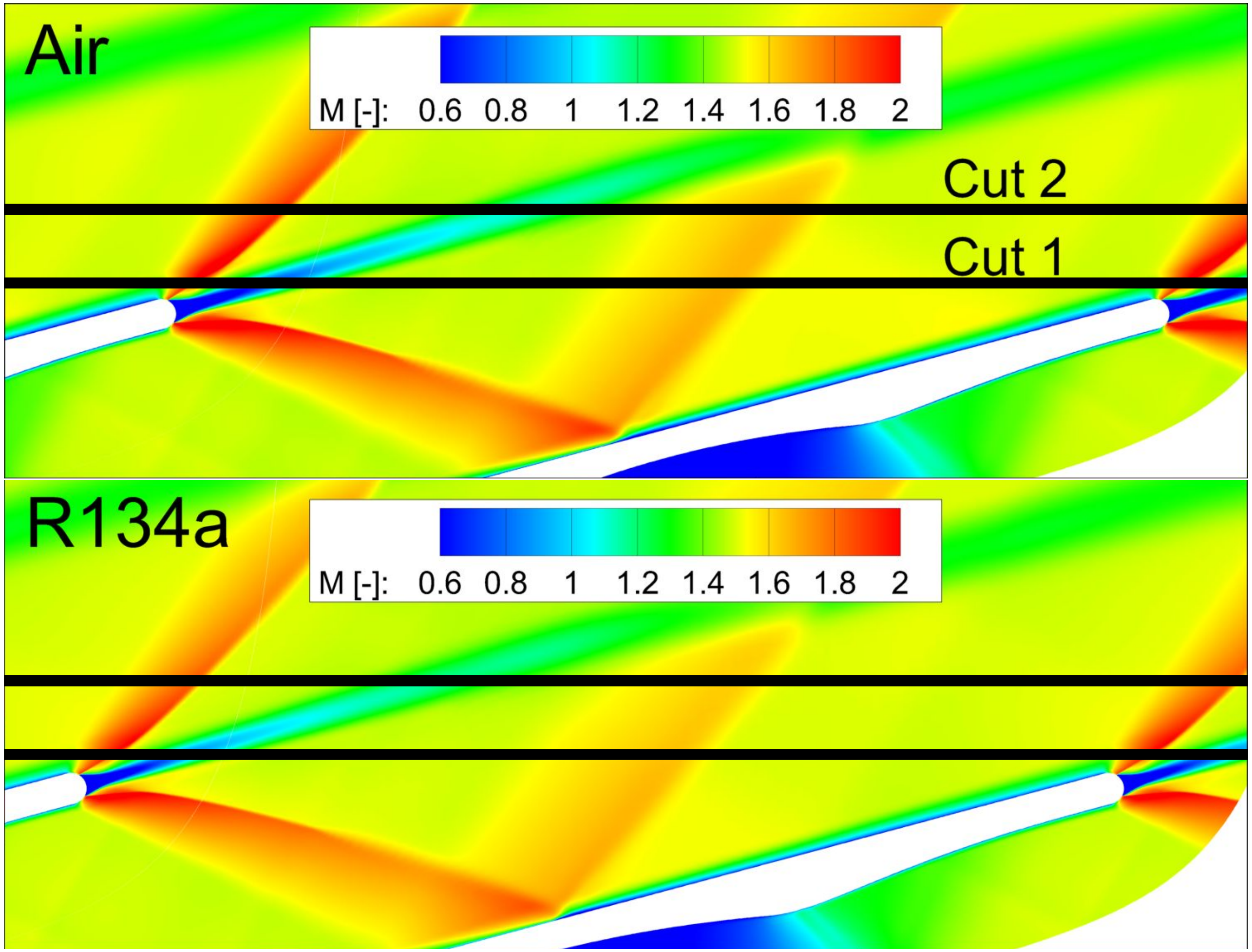
Effect on Wake at Constant exit Mach Number



Distribution of Mach number at trailing edge

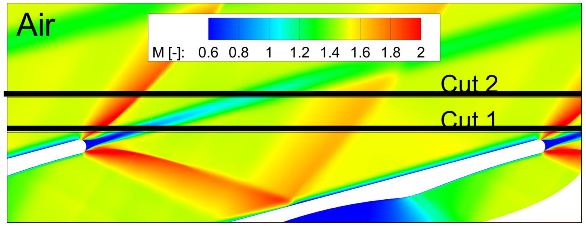
- Isolines at $M = 0.5$ and $M = 1.0$
- Smaller separated base region for R134a
- Occurs due to more flow turning around TE

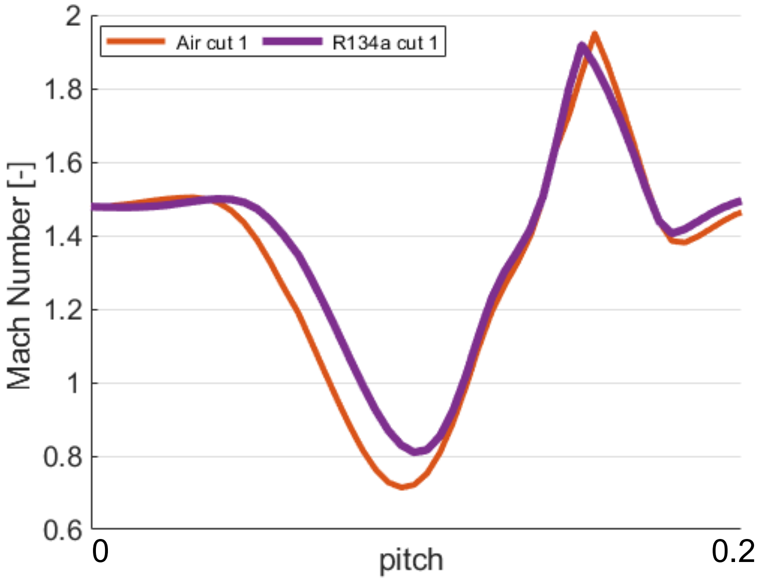
Effect on Wake at Constant exit Mach Number

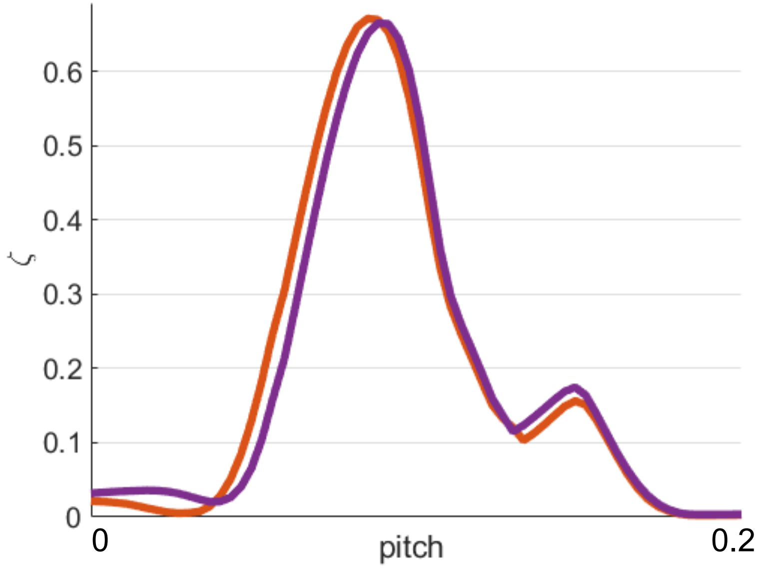


Distribution of Mach number

Effect on Wake at Constant exit Mach Number

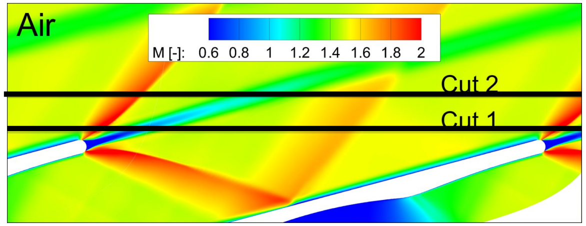


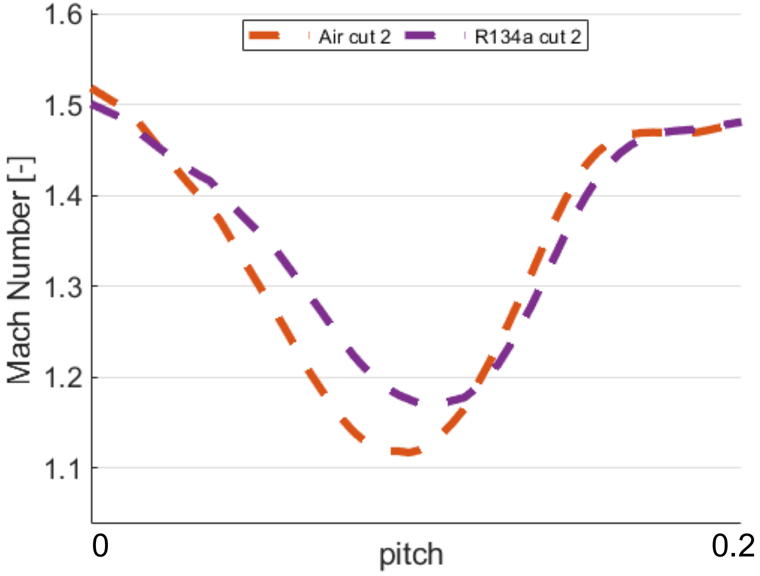


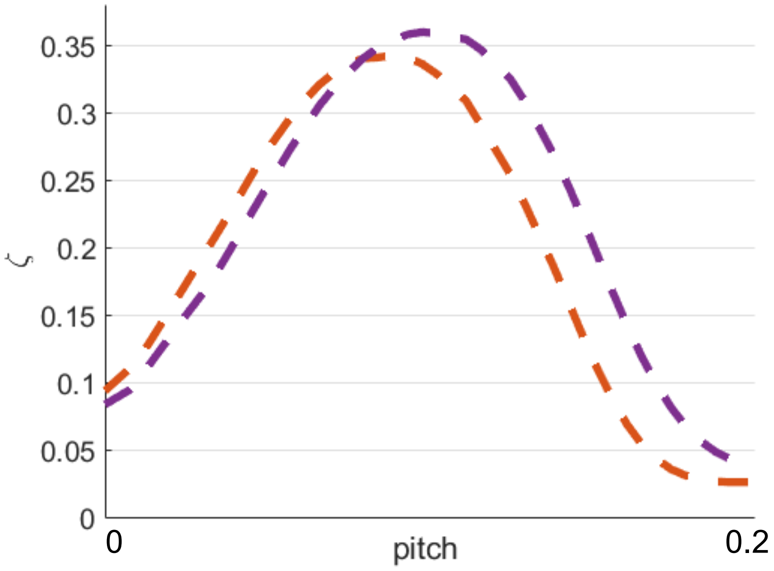


- At cut 1 lower k leads to narrower and shallower wake
- This is due to smaller separated base region
- Loss coefficient is the same for the fluids

Effect on Wake at Constant exit Mach Number

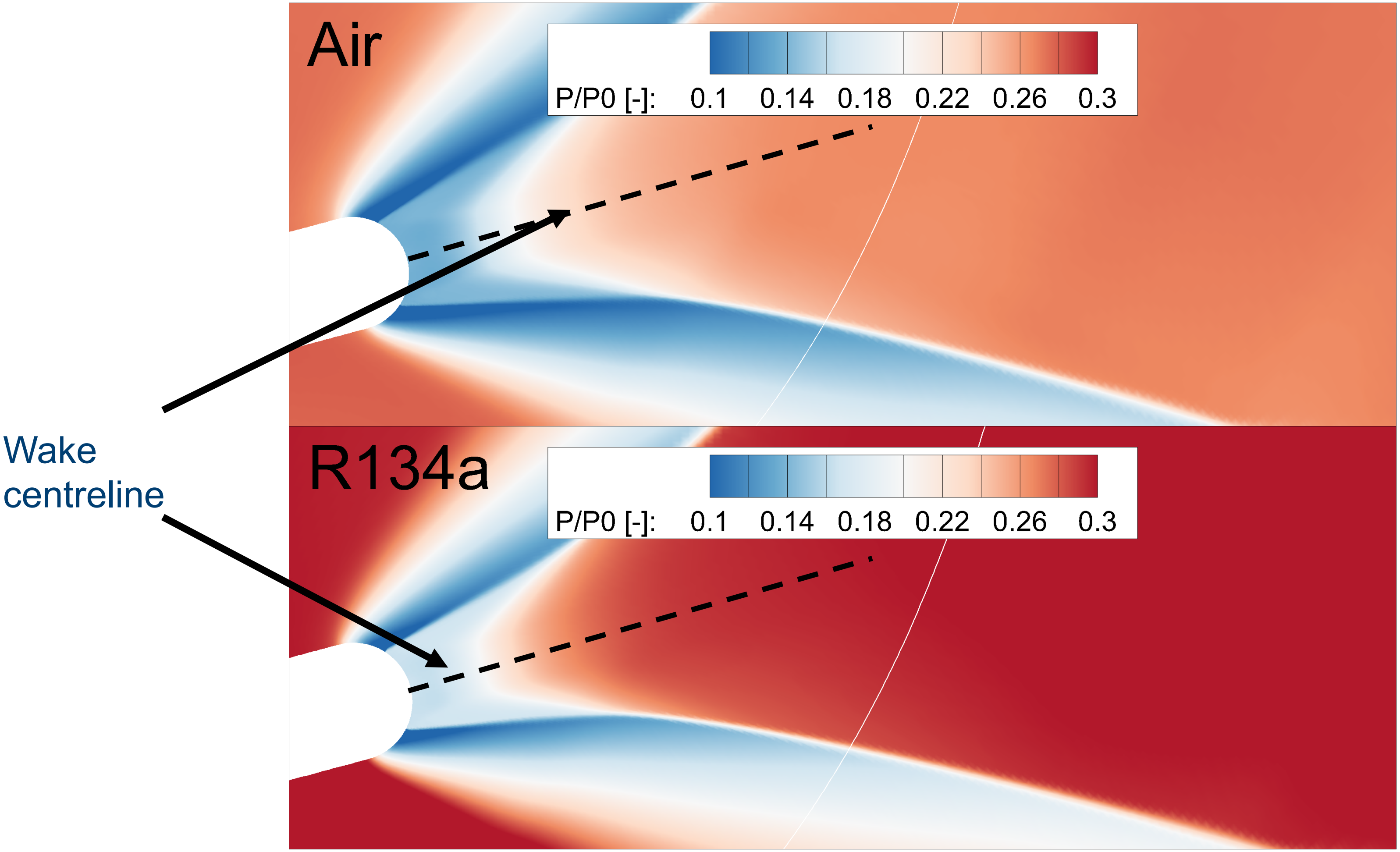






- At cut 2, the wake is still narrower and shallower
- However, loss coefficient has increased for R134a compared to air

Effect on Wake at Constant exit Mach Number



- R134a wake is subject to a larger pressure gradient along wake centreline
  - At constant M_{exit} lower k will have higher pressure at outlet
- Larger adverse pressure gradient and hence more loss

Conclusions

Conclusions

- Reported first-of-their-kind supersonic R134a vane wake measurements
- Open-source geometry and data for use as a validation case - contact aw329@cam.ac.uk
- At constant exit Mach number:
    - Wake becomes shallower and narrower at lower isentropic exponent
    - Larger adverse pressure gradient in wake drives higher loss for lower isentropic exponent

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QUESTIONS

References

- 1. D. Baumgärtner, J. J. Otter, and A. P. S. Wheeler. The Effect of Isentropic Exponent on Transonic Turbine Performance. Journal of Turbomachinery, 142(8), 07 2020. 081007.

- 2. Durá Galiana, F. J. et al. "A Study of Trailing-Edge Losses in Organic Rankine Cycle Turbines." ASME. *J. Turbomach*. 2016;