The Development of a Generic Working Fluid Approach for the Determination of Transonic Turbine Loss

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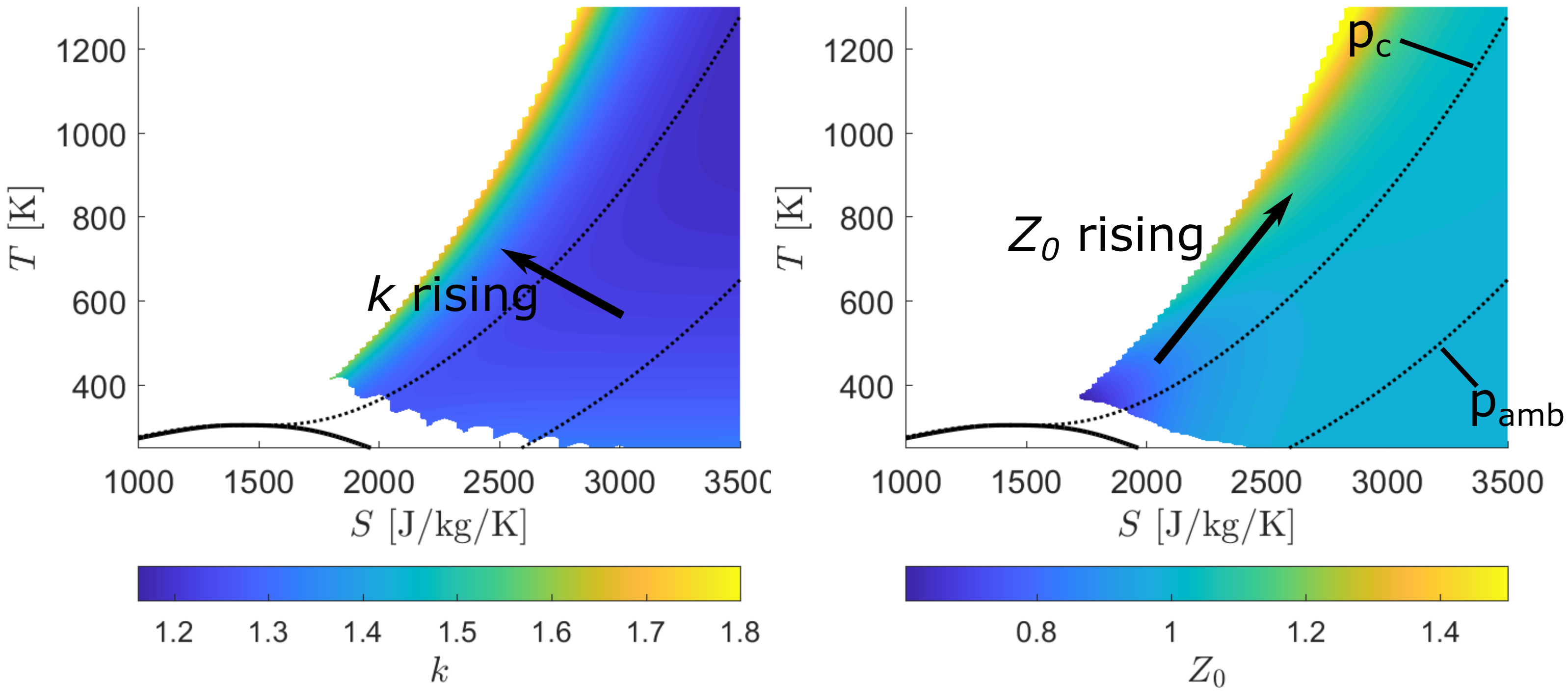
Whittle Laboratory

Non-ideal Turbine Operating Conditions



Contours of Isentropic Exponent and Compressibility Factor for CO2
$(\boldsymbol{M_{exit}} = \mathbf{1.3})$

- Heat recovery and ORCs feature a variety of working fluids and operating points
- Fluid properties and inviscid gas dynamics will vary across T-S space
- How does turbine loss vary across this space?

Turbine Loss Correlations

- In preliminary design phase, loss correlations are used

$$\zeta = f(\phi, \psi, \Lambda, M_{exit}, Re)$$

- Are these applicable to heat recovery and ORC turbines?

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$$\zeta = f(\phi, \psi, \Lambda, M_{exit}, Re, \underbrace{Z_0, k})$$

Impact on loss not known

Research Overview

Research Aim

- Form a reduced order model for turbine loss that is fluid independent

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- Develop a generic approach to evaluate loss
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Non-dimensional Parameters

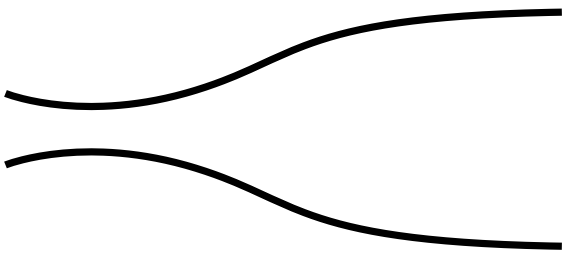
Three non-dimensional parameters were explored within this study:

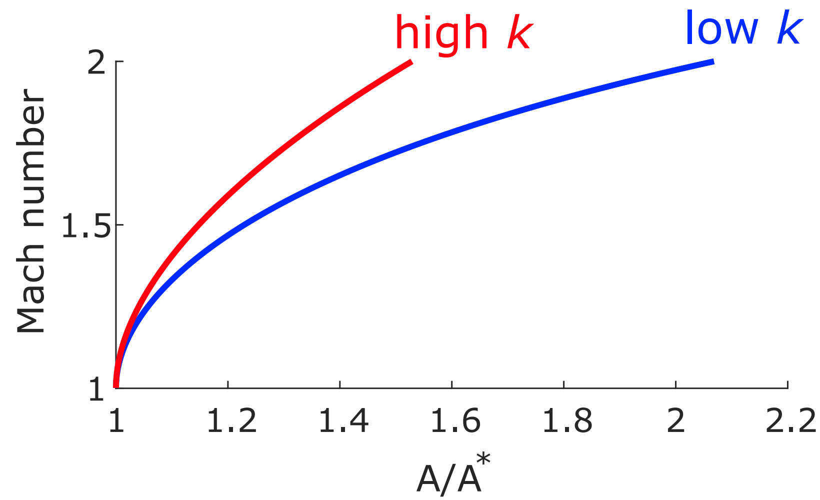
- Exit Mach Number : $$M_{exit}$$
- Inlet Compressibility Factor : $$Z_0 = \frac{p_0}{\rho R_s T_0}$$
- Isentropic Exponent : $$k = log\left(\frac{p}{p_0}\right)/log\left(\frac{\rho}{\rho_0}\right)$$

Non-dimensional Parameters

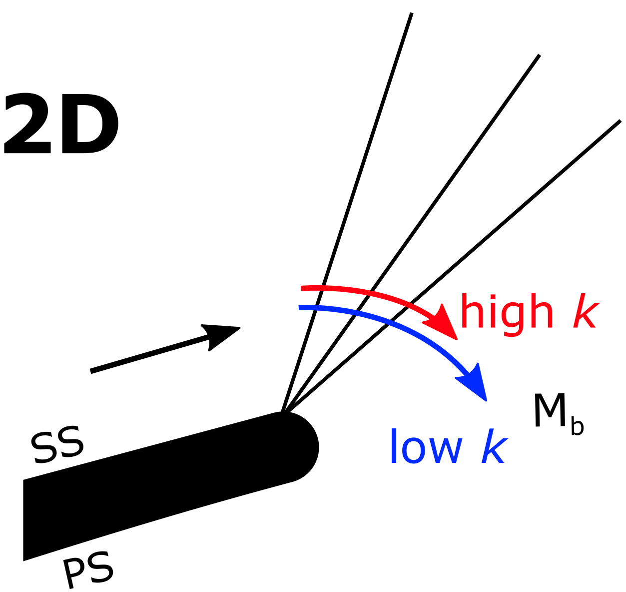
1D

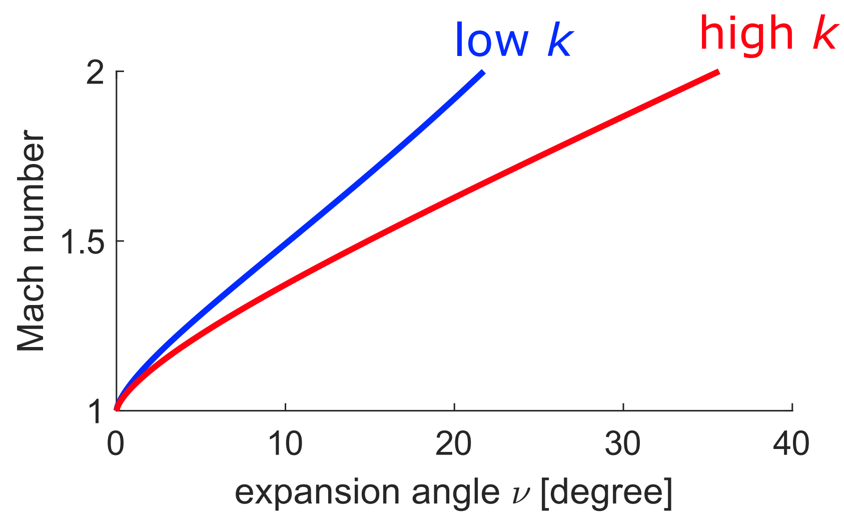
converging-diverging nozzle





2D





Thermodynamic Design Space

- Aim is to create a design space where Z_0 and k can be varied independently
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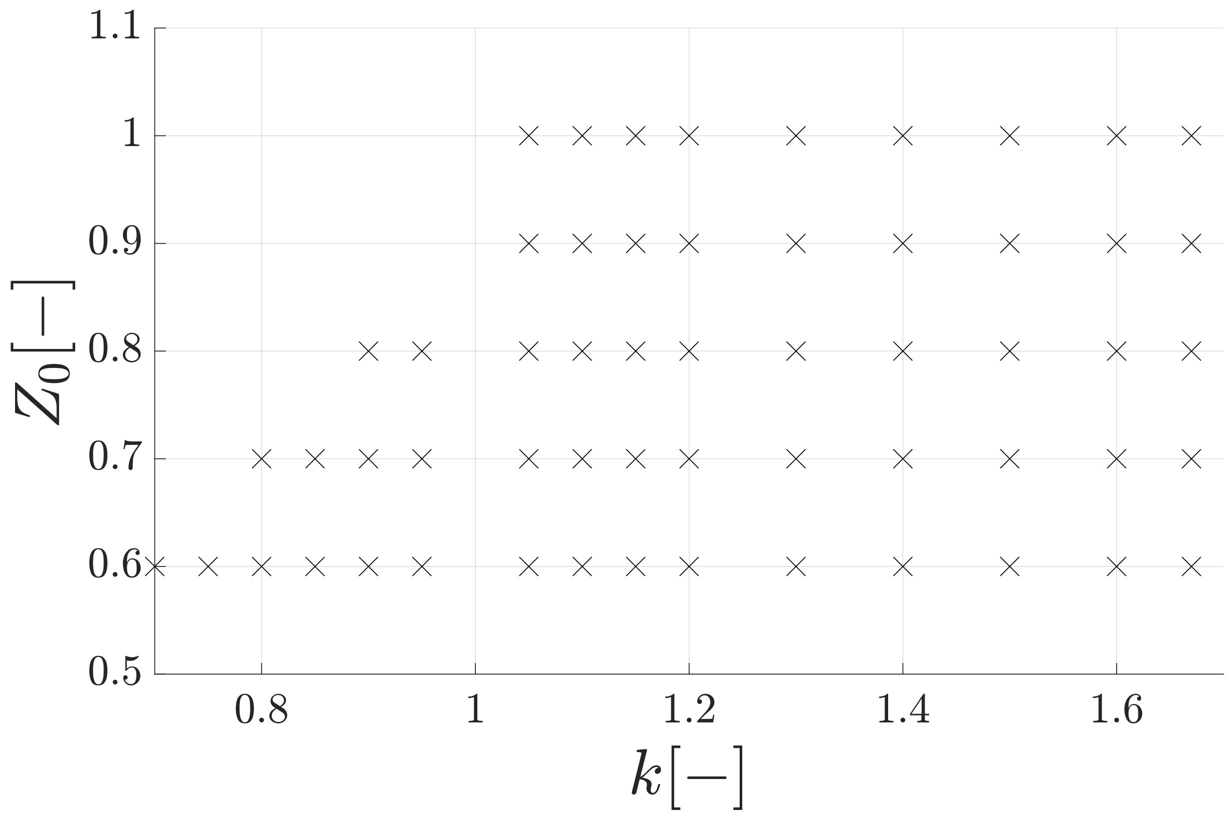

Example design space at $M_{exit} = 1.1$

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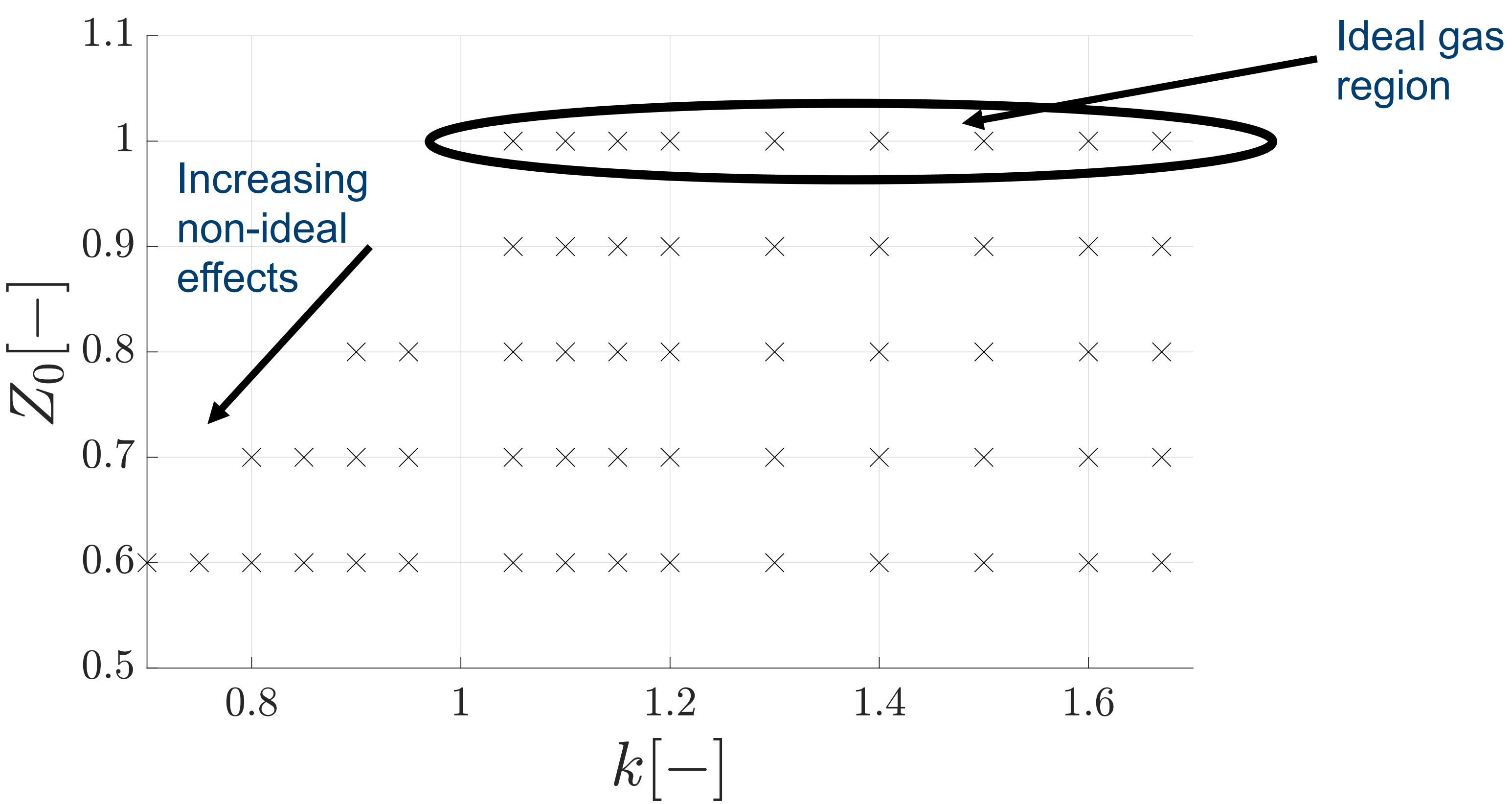


Example design space at $M_{exit} = 1.1$

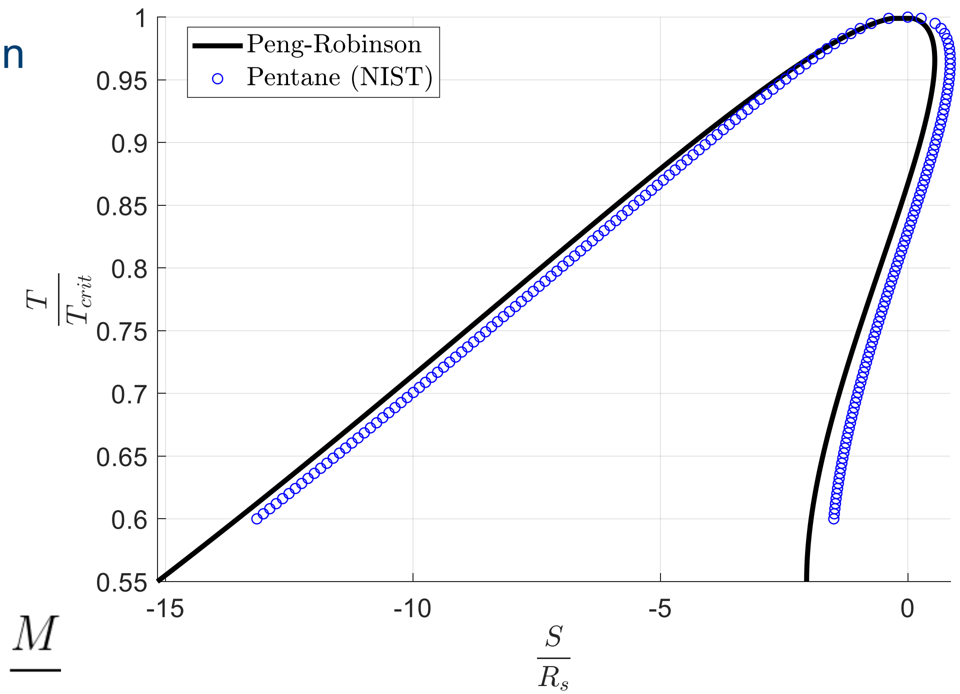
Peng-Robinson Equation of State

- Fluid modelled with Peng-Robinson equation of state
- Ideal heat capacity modelled as polynomial
- Produces realistic saturation dome
- Approach based on the generalised ORC studies of White et al.[1]

$$p = \frac{RT}{V_m - b} - \frac{a\alpha(\omega, T)}{V_m^2 + 2bV_m - b^2} \qquad V_m = \frac{M}{\rho}$$

$$a = \frac{0.45724 R^2 T_{cr}^2}{p_{cr}}; b = \frac{0.0778 R T_{cr}}{p_{cr}}$$

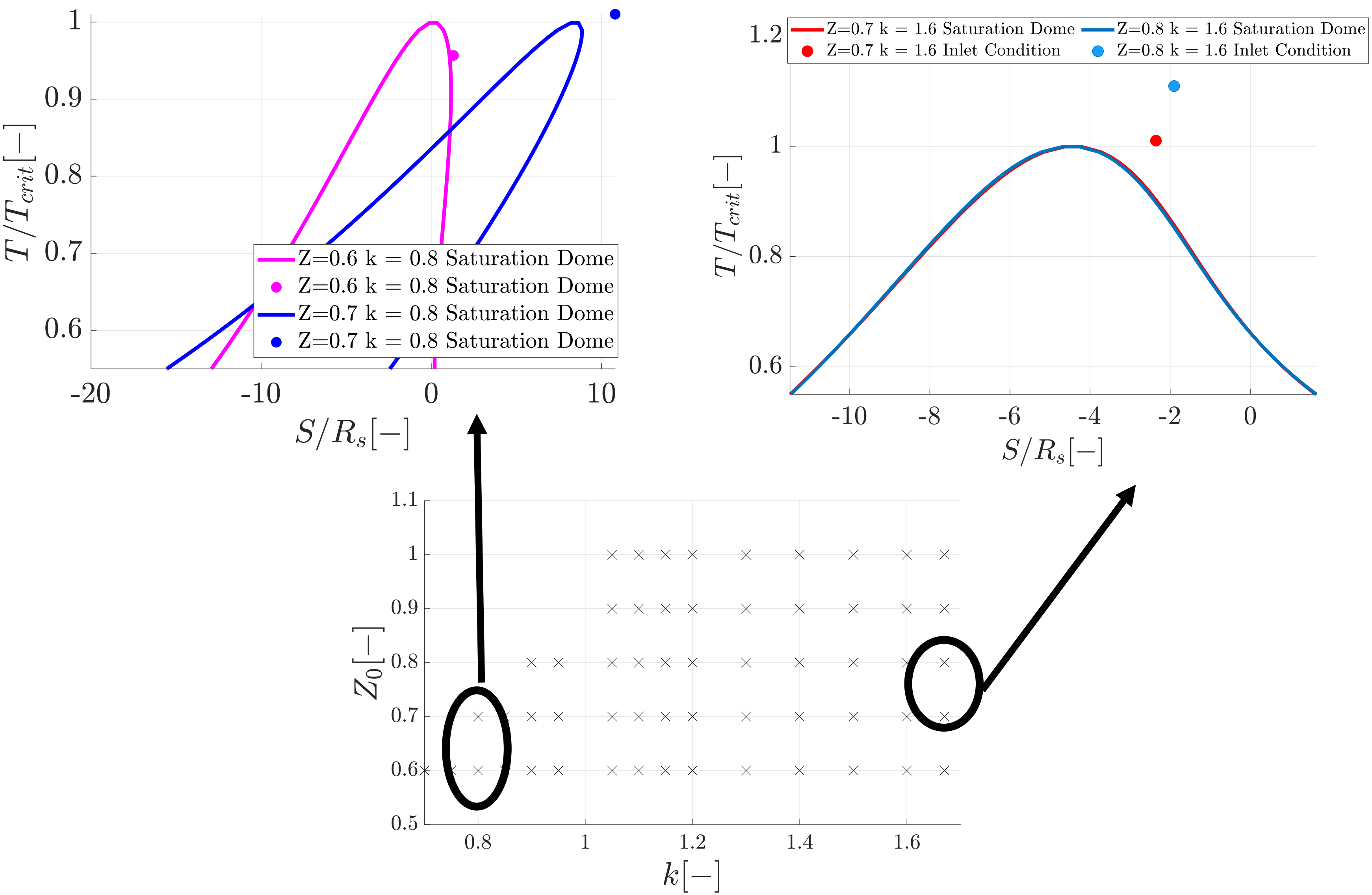
$$\frac{c_p^{ideal}}{R_s} = A + BT + CT^2$$



Example T-s Diagram

1. M. T. White and A. I. Sayma. A generalised assesment of working fluids and radial turbines for non-recuperated subcritical organic rankine cycles. Energies, 11 (4), 2018.

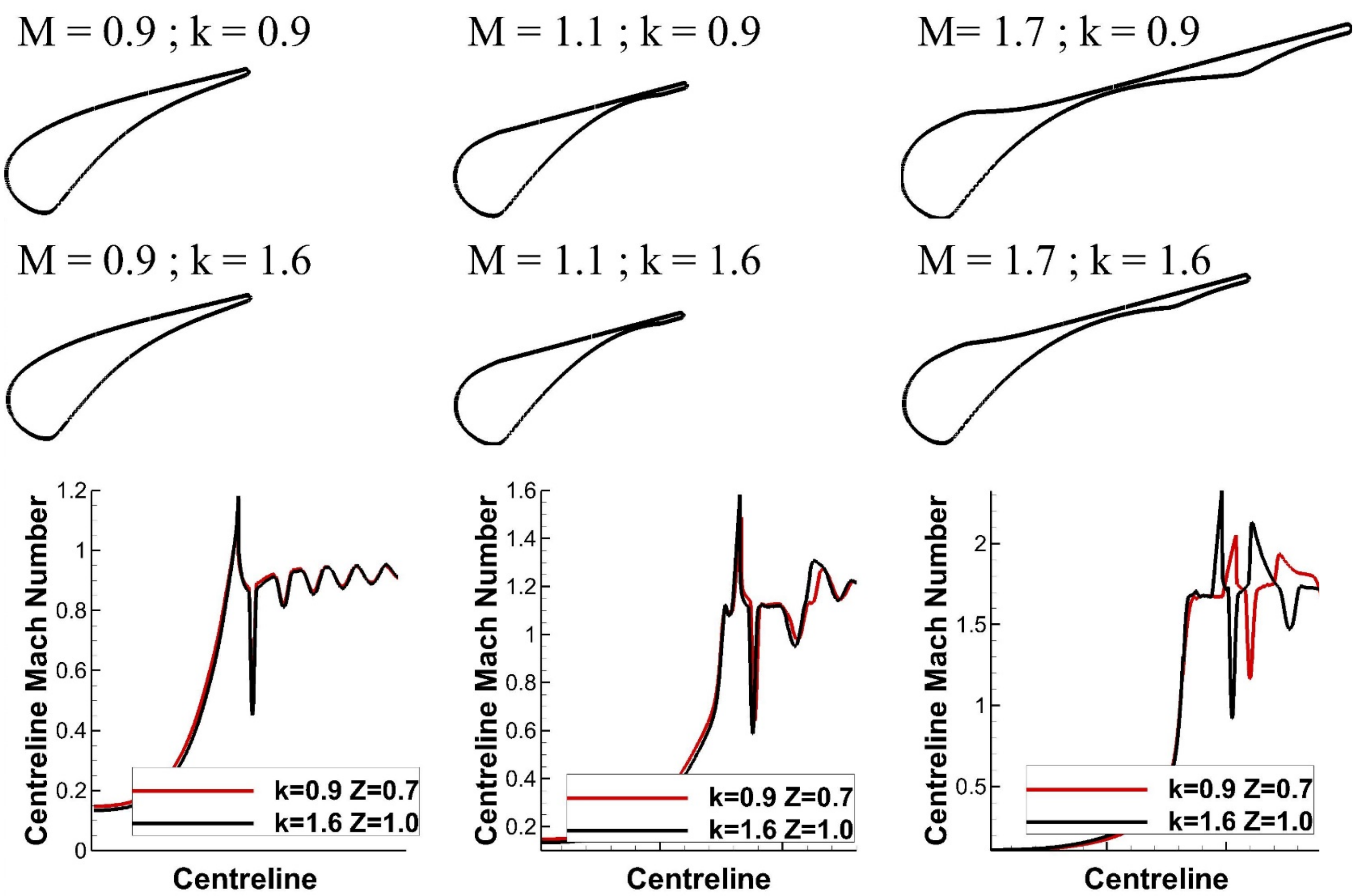
Thermodynamic Design Space



Non-dimensional Parameters

- Transport properties not given by EOS
- Constant parameters:
  - Exit Reynolds number : $$\frac{\rho V c}{\mu} = 1.7 \times 10^6$$
  - Exit Prandtl number : $$\frac{c_p \mu}{\alpha} = 0.7$$
- Molecular viscosity and thermal conductivity varied for each fluid
- Take to be constant throughout flow field i.e. no temperature variation

Geometry Generation



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

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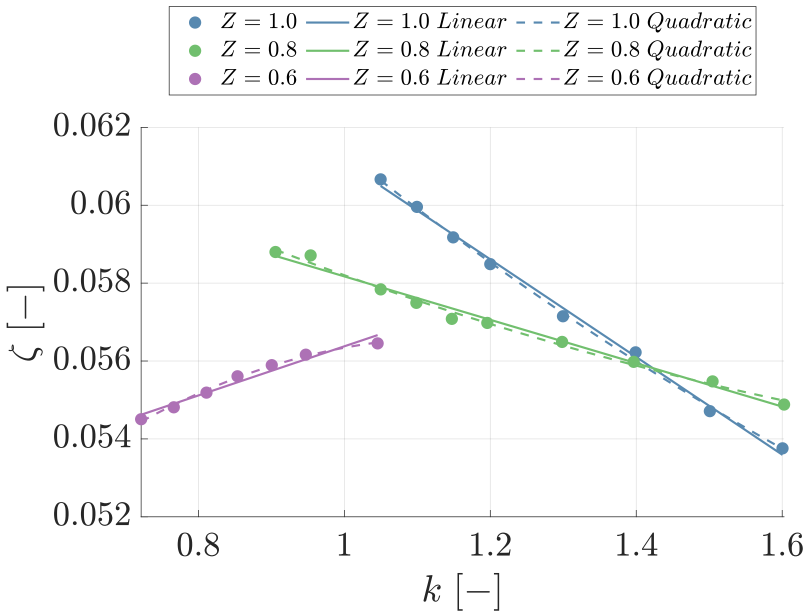
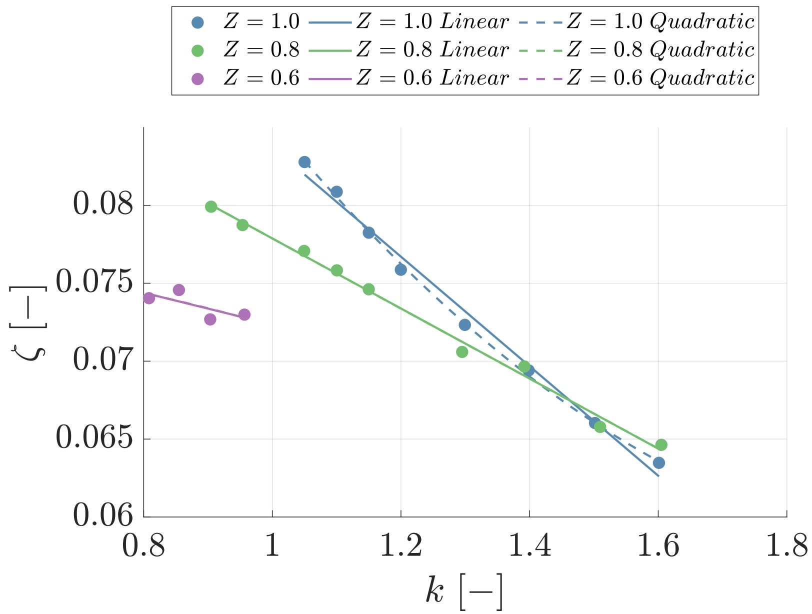
Variation of Loss Coefficient with k



$M_{exit} = 0.9$

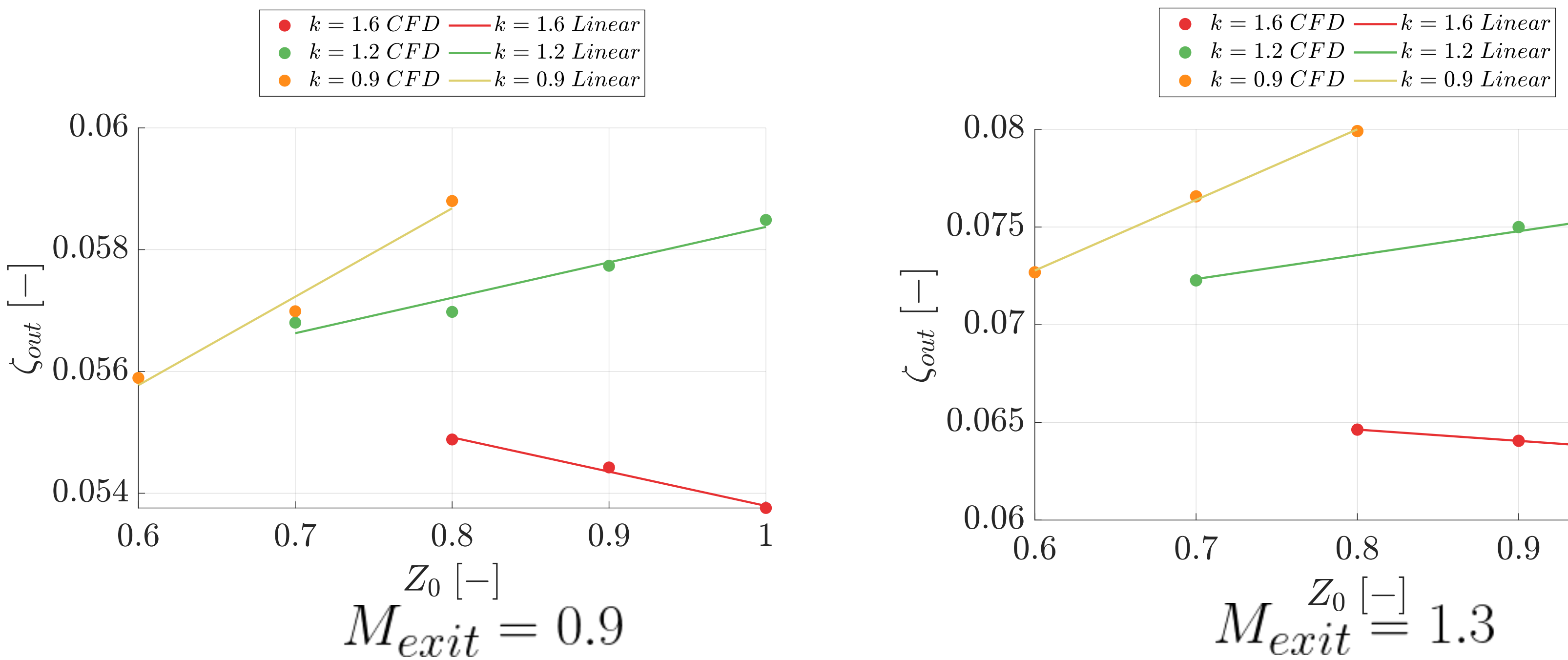


$M_{exit} = 1.3$

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

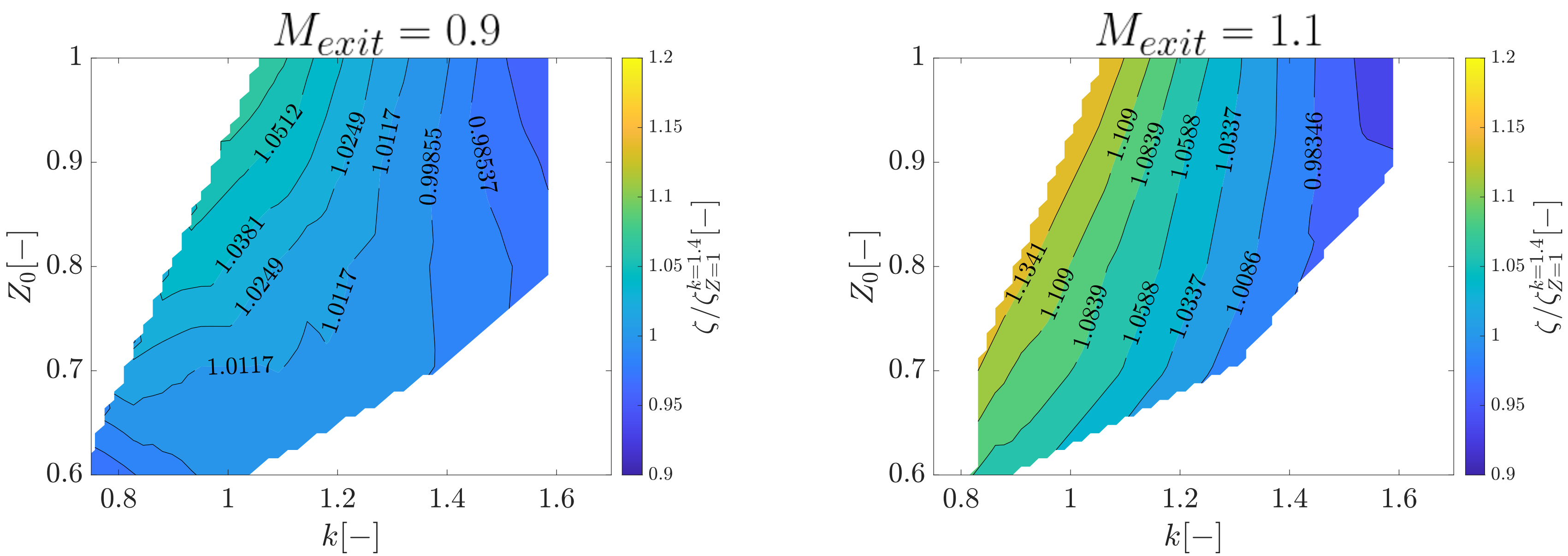
- Greater variation in loss at higher exit Mach number
- At Z_0 = 0.8 and 1.0 the loss forms linear monotonic function of k
- Loss becomes less sensitive to k as Z_0 is reduced
- At Z_0 = 0.6 non-monotonic behavior is observed for $M_{exit} = 0.9$
- In general - low k means higher loss

Variation of Loss Coefficient with Z



- Lower variation in loss with Z_0 compared to k
- Qualitative behaviour is identical between exit Mach numbers
  - At k = 1.6 low sensitivity to Z_0
  - Otherwise, low Z_0 leads to lower loss

Variation of Loss Coefficient with Mach number



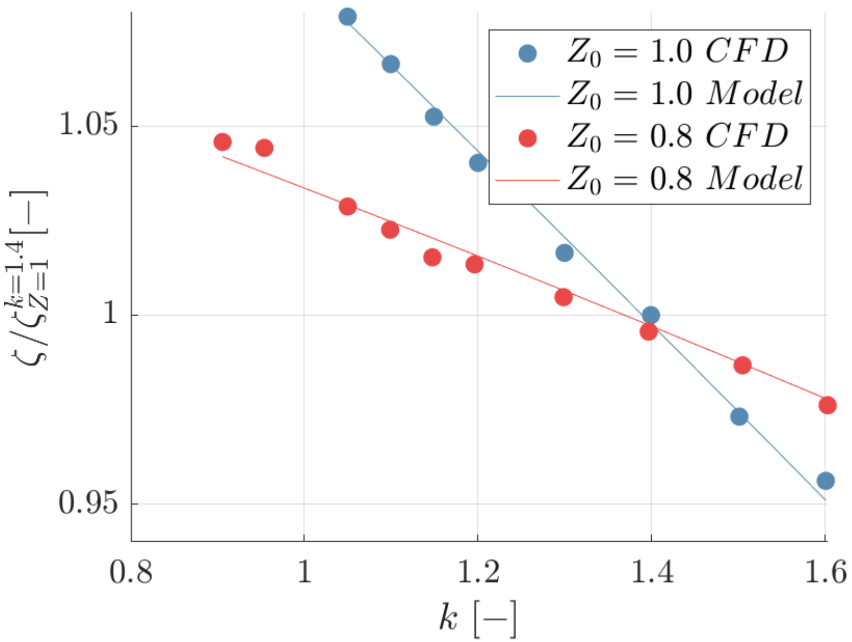
- Loss presented relative air (k=1.4, Z_0=1)
- Variation between -2 and 1% for $M_{exit} = 0.6$
- Maximum loss at Z_0=1 k=1.05

Impact on Turbine Design

- Correlation defined for each value of M_{exit}

$$\zeta / \zeta_{Z_0=1}^{k=1.4} = \alpha_{00} + \alpha_{10}k + \alpha_{01}Z_0 + \alpha_{20}k^2 + \alpha_{11}kZ_0 + \alpha_{02}Z_0^2$$

- RMSD values between 0.6 and 3.2 % - appropriate for preliminary estimate



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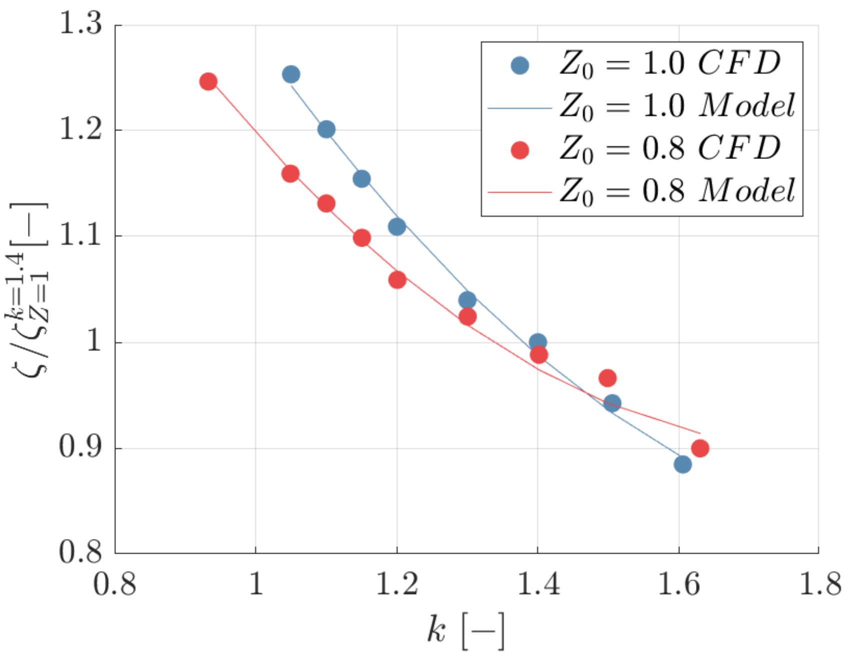
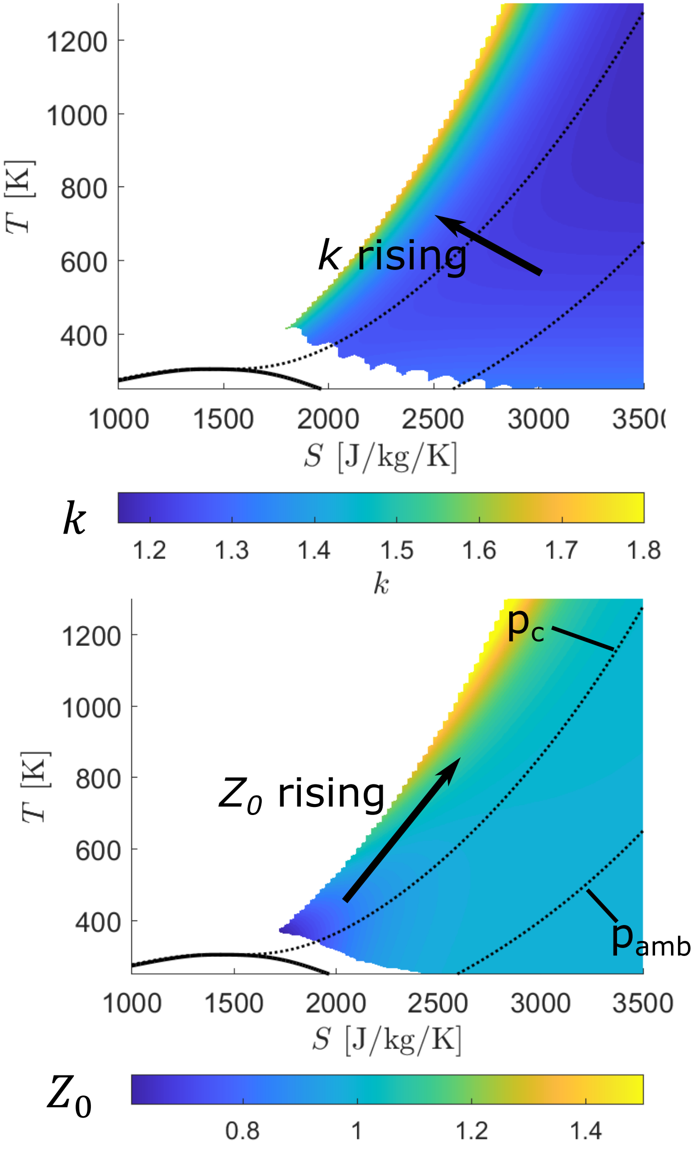
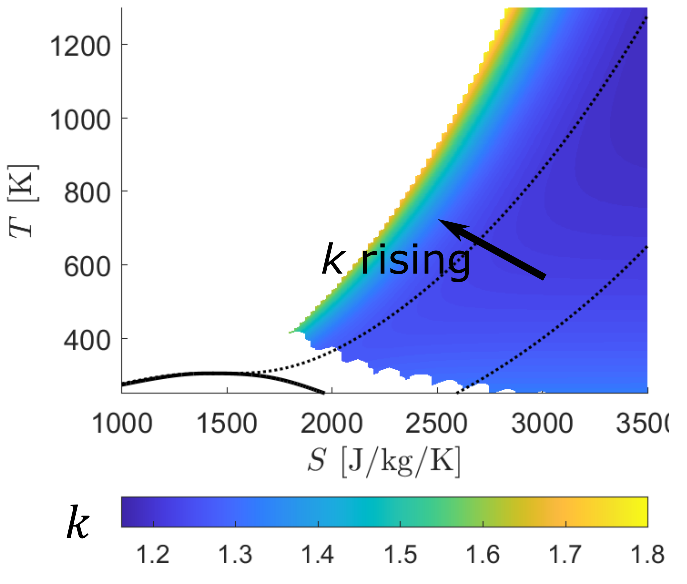


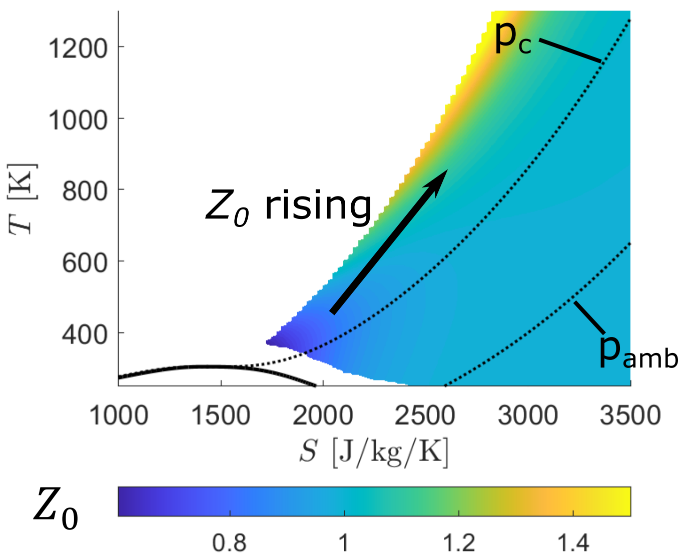
$M_{exit} = 1.7$

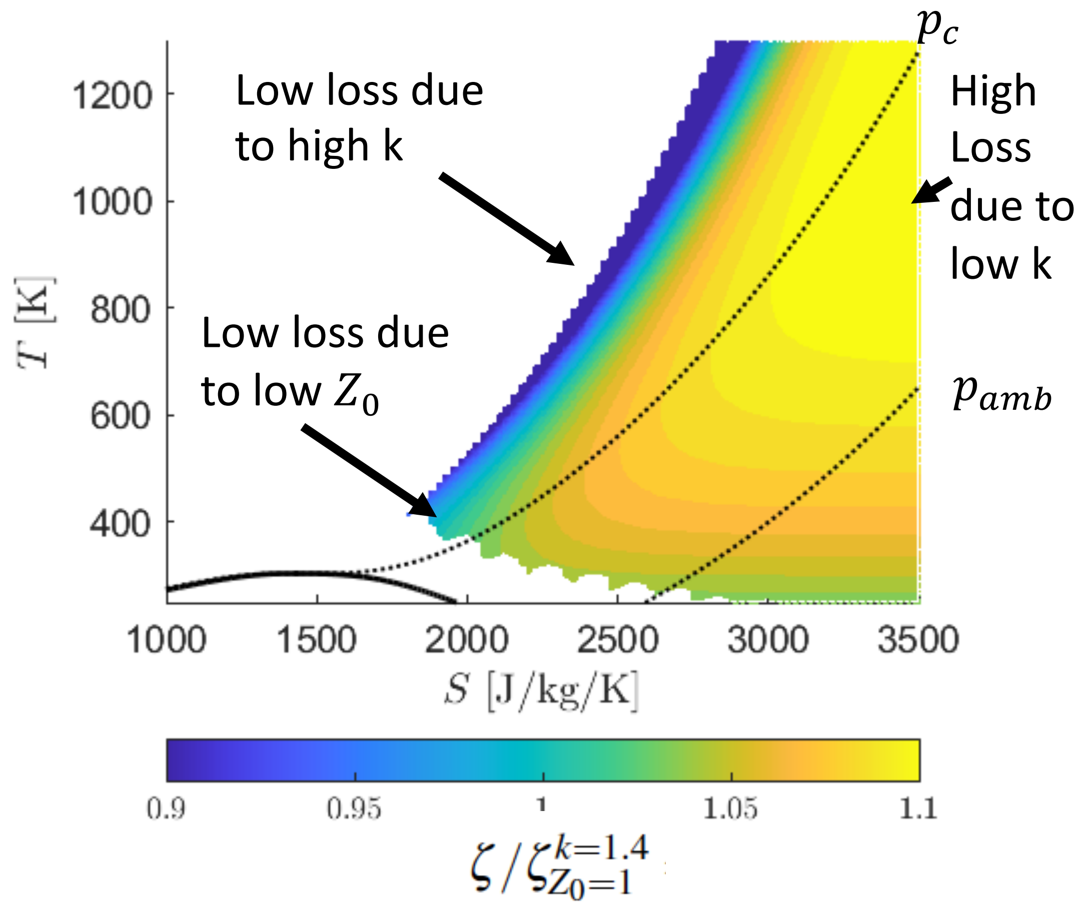
Example Application



Example Application







- Example loss variation for CO2 at $M_{exit} = 1.3$
- Loss region at supercritical conditions due to high k
- Higher loss towards ambient pressure due to low k
- Reduced loss near critical point due to low Z_0

Conclusions

Conclusions

- A fluid-independent method for turbine performance has been developed
- Generalised points about loss generation
  - Loss increases with reduced isentropic exponent
  - Loss reduces with reduced compressibility factor
- Potential to reduce turbine loss through fluid choice and operating point

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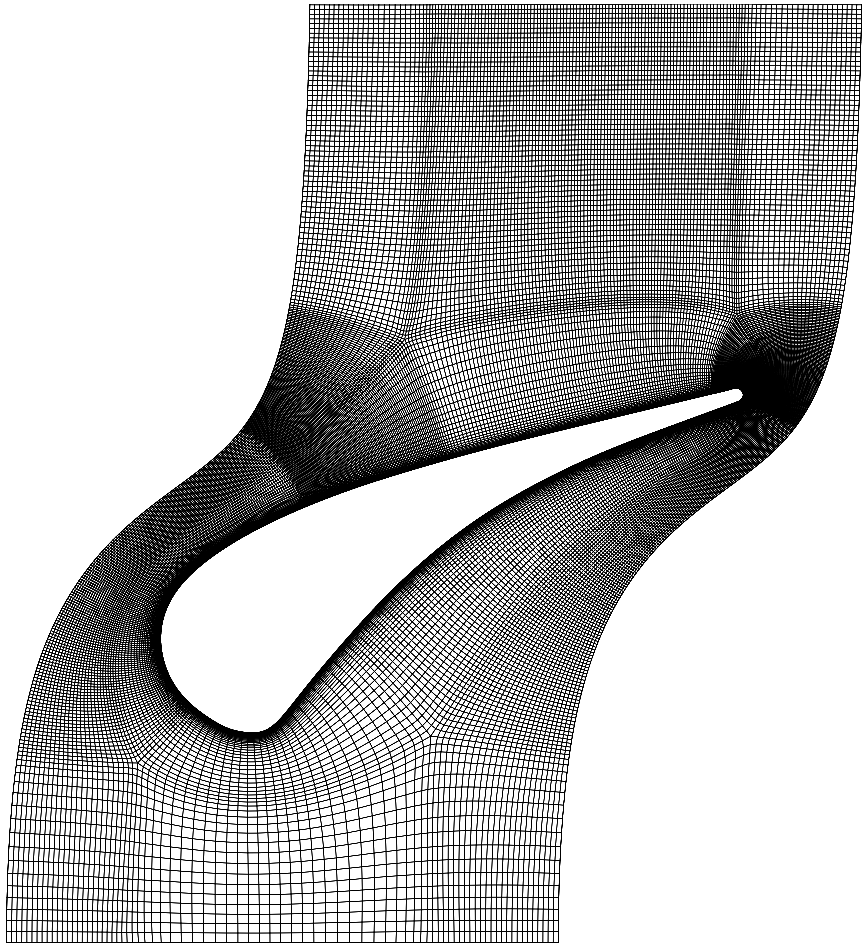
- This work was supported by the EPSRC (EP/L027437/1) and computational resources were provided by EPSRC Tier-2 capital grant EP/P020259/1
- The authors would like to thank the reviewers for their insightful comments and valuable feedback
- In addition the authors would like to thank the organizing committee

QUESTIONS

APPENDIX

Computational Setup

- 2D RANS simulations undertaken with FLUENT v17.0
- Spalart-Allmaras turbulence model with wall functions
- Thermodynamic modelling achieved with built-in PR model
- Previously validated and verified by Baumgärtner et al.



Mesh for $M_{exit} < 1.0$

Loss coefficient

- Loss coefficient defined based on a constant pressure mixed-out state
- $\zeta = H - H_s / Ho - H_s$
- H : enthalpy at mixed-out state
- Hs : enthalpy achieved at mixed-out pressure under isentropic conditions
- H0: Total enthalpy at inlet of domain

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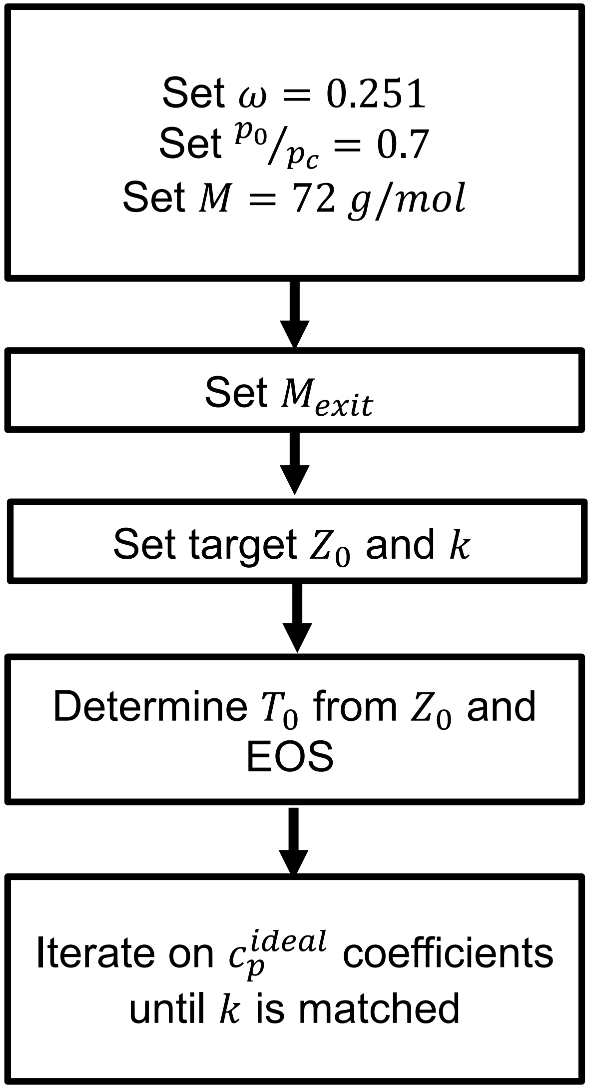

- Aim is to create a design space where Z_0 and k can be varied independently
- As Z_0 and k are thermodynamically linked multiple fluids required
- Z_0 range from 0.6 to 1.0
- k range from 0.8 to 1.6
- Acentric factor and molar mass held constant based on pentane
- Reduced stagnation pressure constant at 0.7

$$p = \frac{RT}{V_m - b} - \frac{a\alpha(\omega, T)}{V_m^2 + 2bV_m - b^2} \qquad V_m = \frac{M}{\rho}$$

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