Non-Ideal Effects in Compressible Swirling Flows

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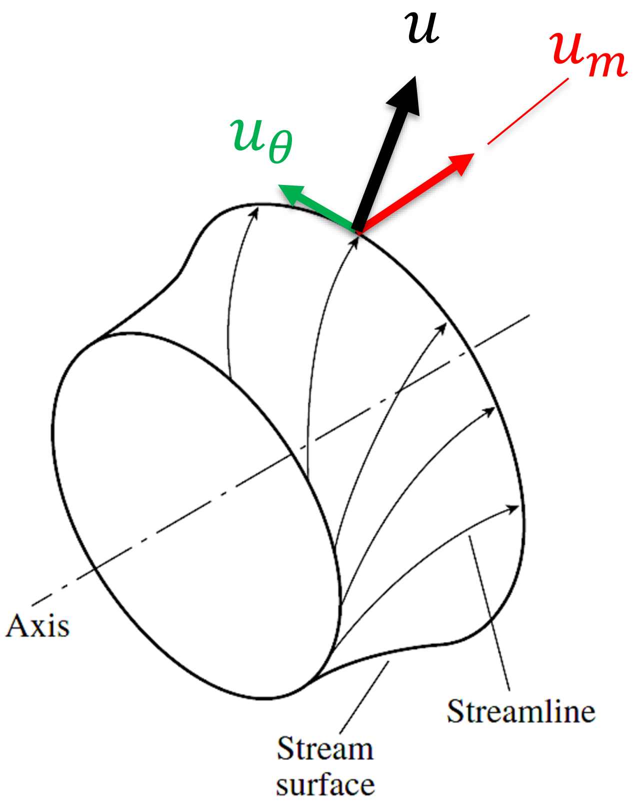
Background

Limited knowledge of NICFD effects on turbomachinery

- efficiency
- **operability**

choking   instability

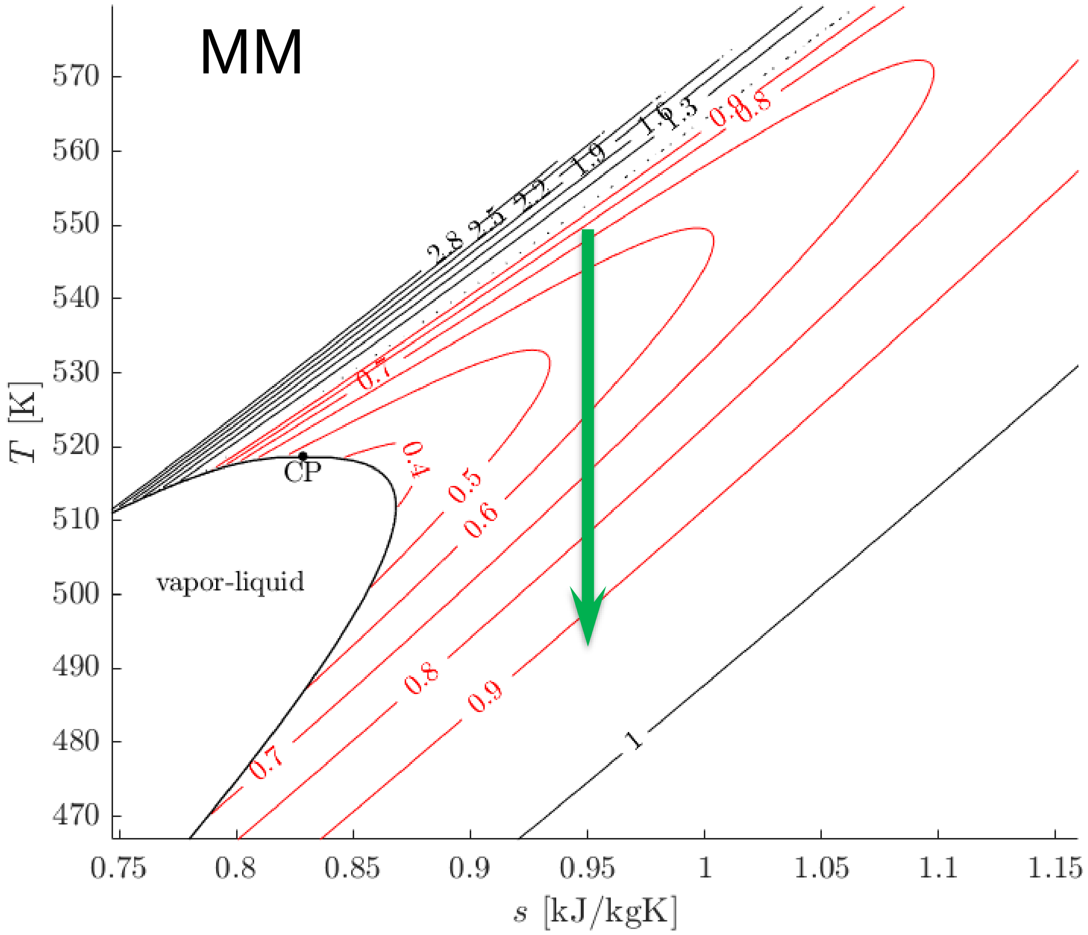


NICFD effects: isentropic exponent γ_{pv}

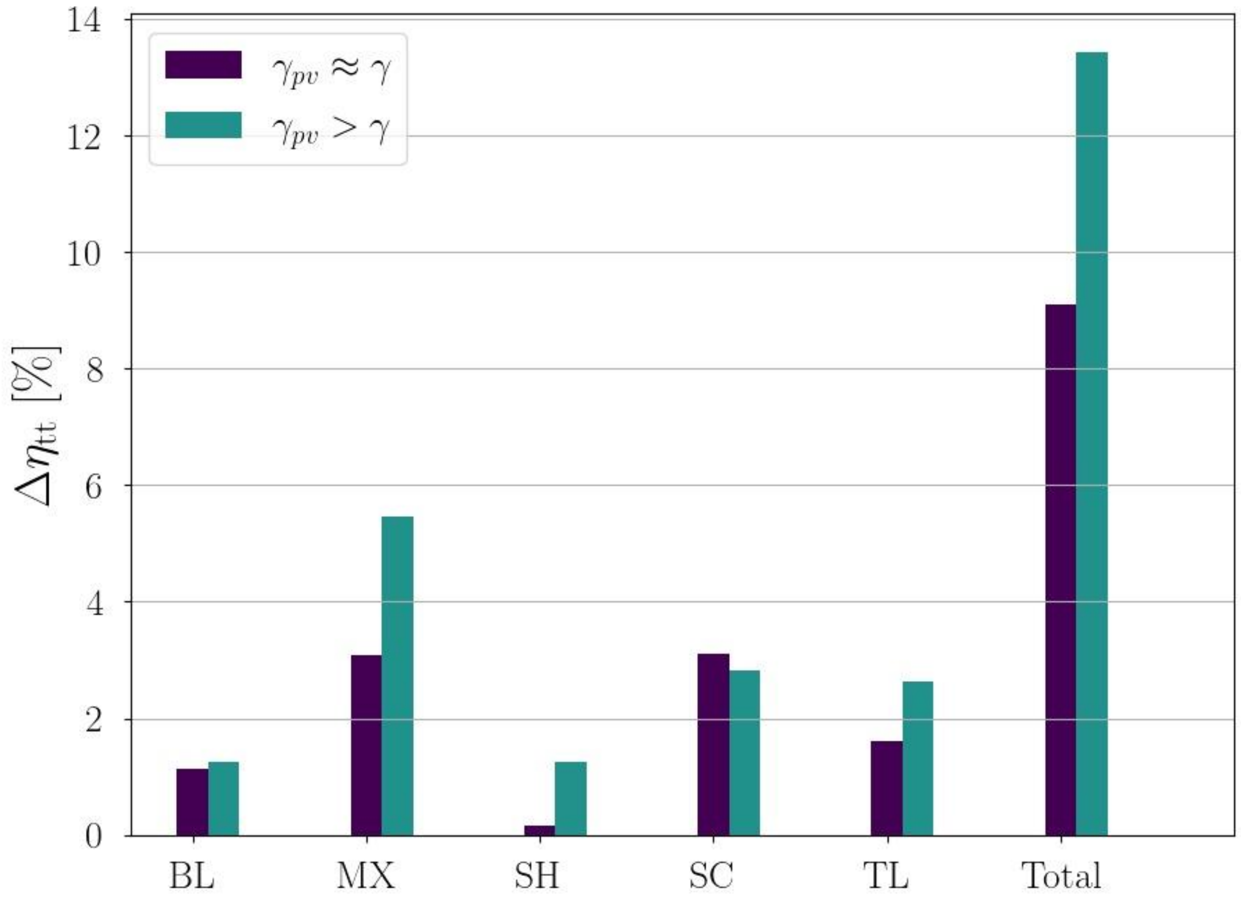
$$\gamma_{pv} = -\frac{v}{p}\left(\frac{\partial p}{\partial v}\right)_s$$

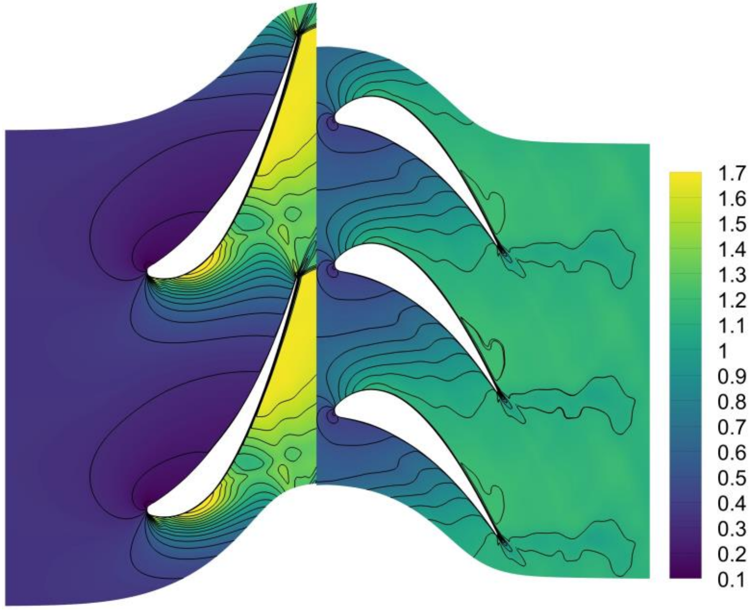
Dilute gas state:

$\gamma_{pv} \rightarrow \gamma$, with $\gamma > 1$



Relevance of NICFD effects on losses





Efficiency can differ of up to $\sim 4\%$

Giuffre' and Pini, "Design guidelines for axial turbines operating with non-ideal compressible flows", JEGTP, 2020, article in press

Problem Statement

No existing knowledge on quantitative impact of NICFD effects on

- **Choking** conditions
- Flow **deviation** in post and pre-expansion processes

Scope of Research

- Assess variation of flow **deviation** as $f(\gamma_{pv})$
- Assess impact of γ_{pv} on **choking** in turbomachinery

Methodology: 2-steps Approach

1

- Theoretical analysis on **Swirling Flow**

2

- Verification and validation through **CFD**

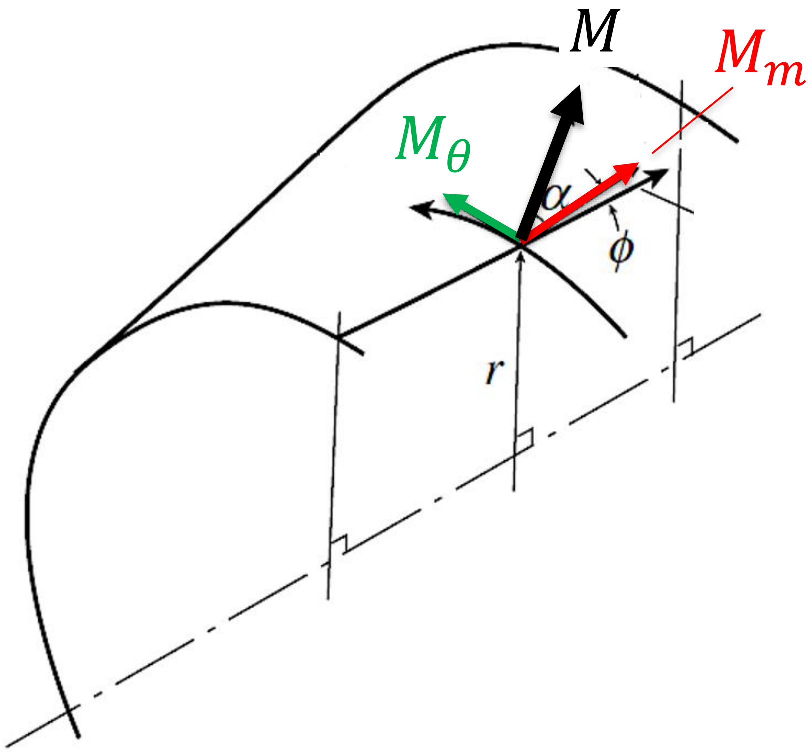
Theoretical Analysis

Corrected mass flow per unit area (1)

$$\dot{m}_{corr} \simeq \frac{M_m}{\left(1 + \frac{\gamma_{pv} - 1}{2} M^2\right)^{\frac{\gamma_{pv}+1}{2(\gamma_{pv}-1)}}}$$

absolute Mach number (M)

$= M \cos\alpha$ meridional Mach number (M_m)



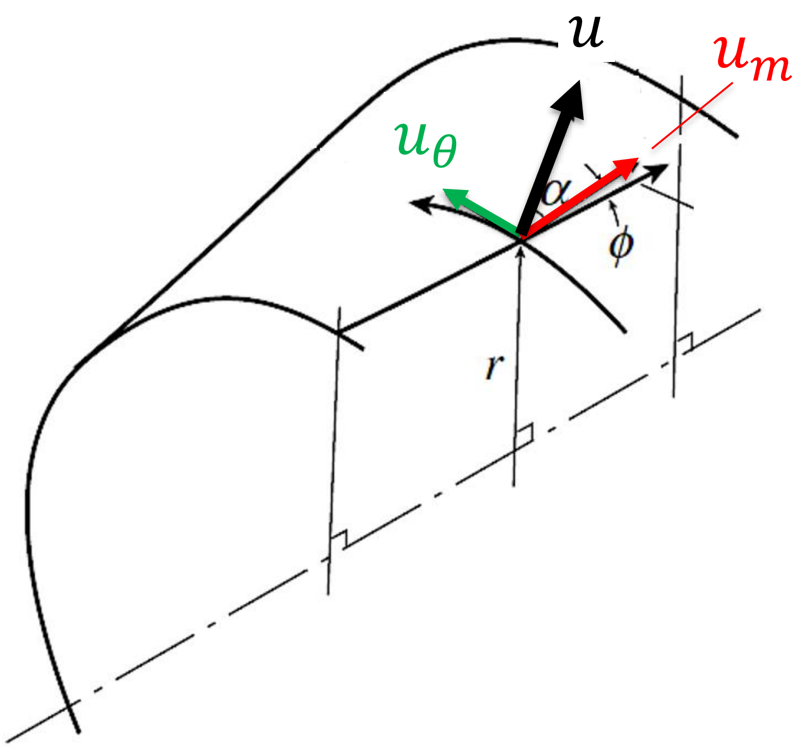
Assumption: $\gamma_{pv} = const$

Corrected mass flow per unit area (2)

$$\dot{m}_{corr} \simeq \left(1+\frac{\gamma_{pv}-1}{2}M^2\right)\sqrt{\frac{M^2}{1+\frac{\gamma_{pv}-1}{2}M^2}-\left(\frac{u_\theta}{\sqrt{\gamma_{pv,t}Z_tRT_t}}\right)^2}$$

absolute Mach number

$= \hat{u}_\theta$ swirl parameter

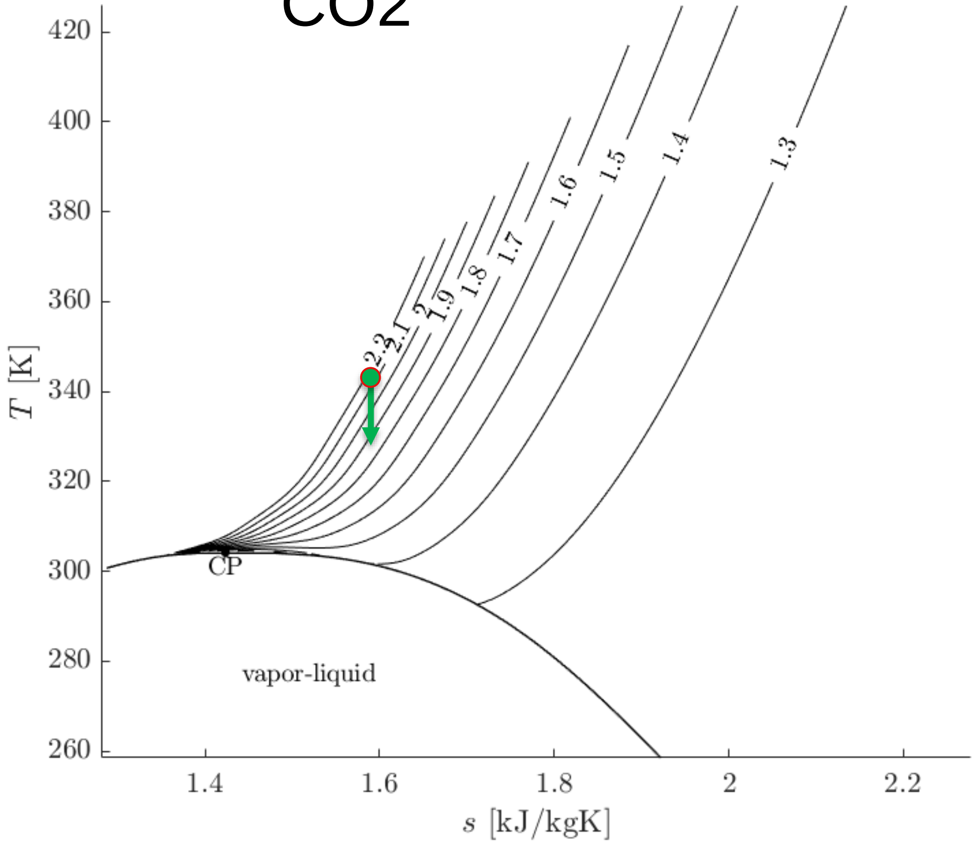


Assumption: $\gamma_{pv} = const$

Investigated Processes

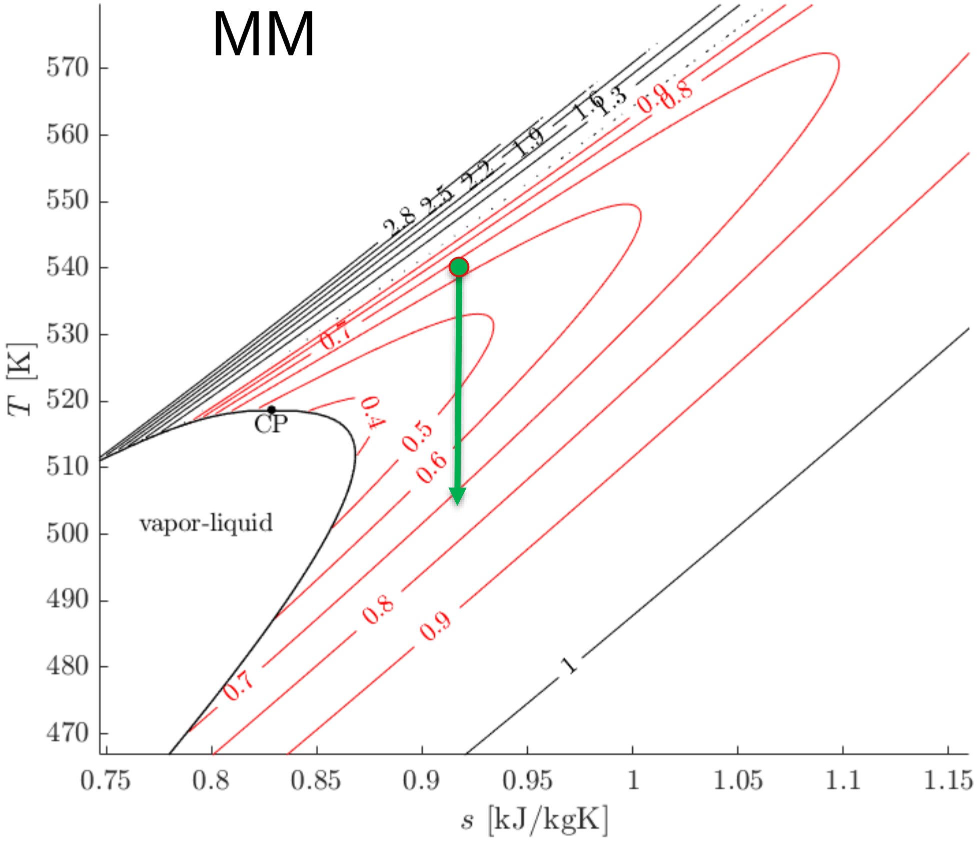
$\gamma_{pv} > \gamma$

CO2

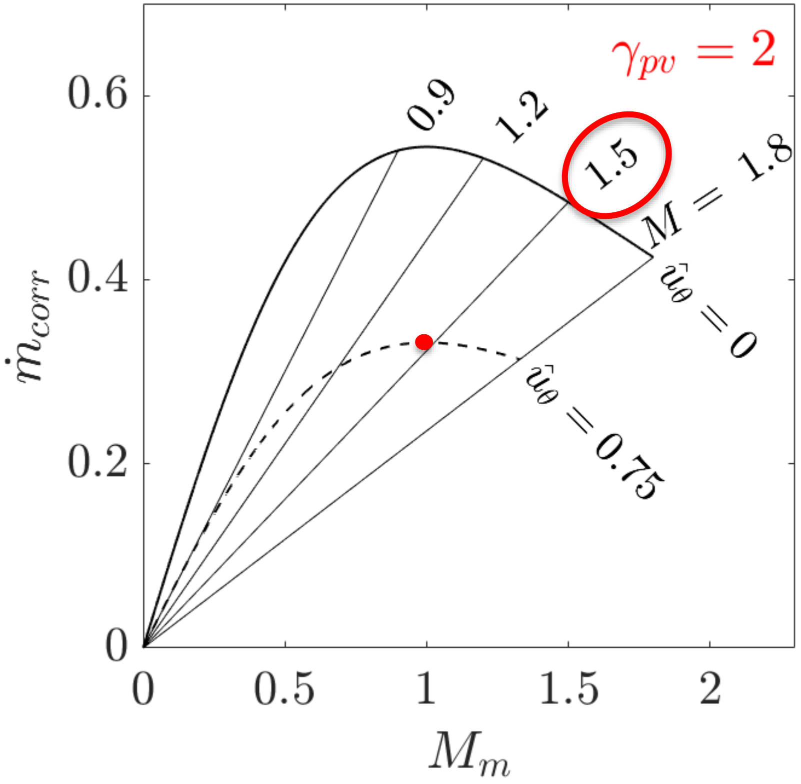


$\gamma_{pv} < \gamma$

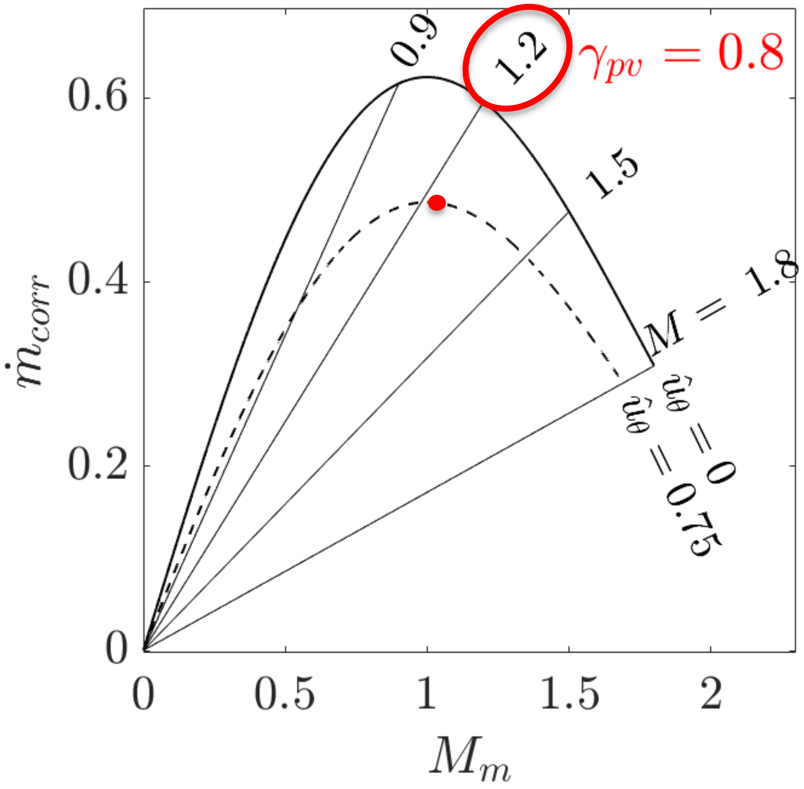
MM



Influence of γ_{pv} on Choking



$\gamma_{pv} > \gamma$



$\gamma_{pv} < \gamma$

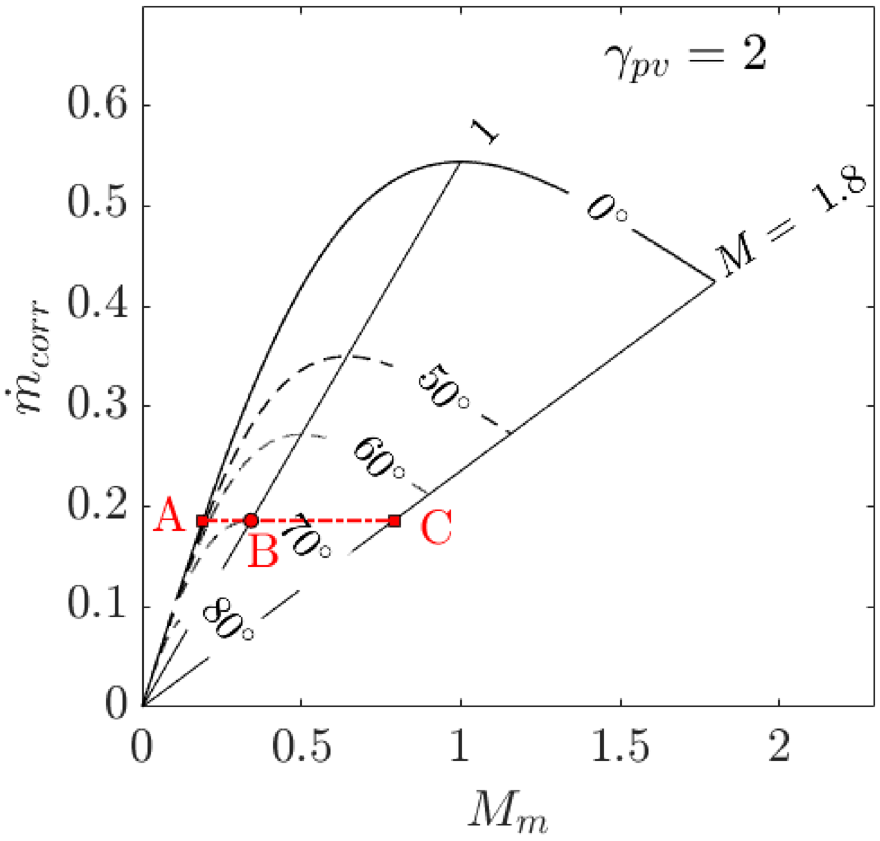
Choking: $M_m = 1$

M ↑ γ_{pv} ↑

Exemplary Post – Expansion in Turbine

Horizontal line at constant $\dot{m}_{corr}$ (A-B-C)

- Point B: sonic throat ($M = 1$)
- Point C: post-expansion final state ($M = 1.8$)
- **Deviation angle increases if γ_{pv} decreases**



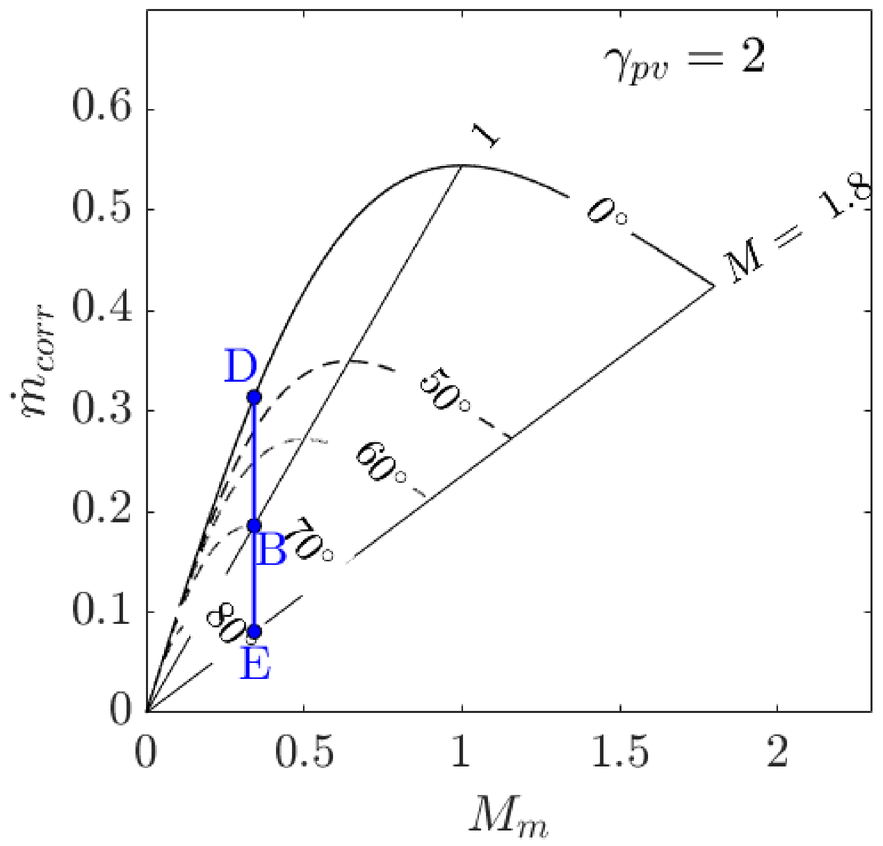
Exemplary Expansion in Supersonic Turbine

Vertical line at constant M_m (D-B-E)

- Constant flow coefficient
- Negligible post-expansion
- **$\Delta \dot{m}_{corr}$ increases if γ_{pv} decreases**

↓

- Larger area variation to accommodate larger volumetric flow ratio $\alpha = \rho_{t,in}/\rho_{out}$



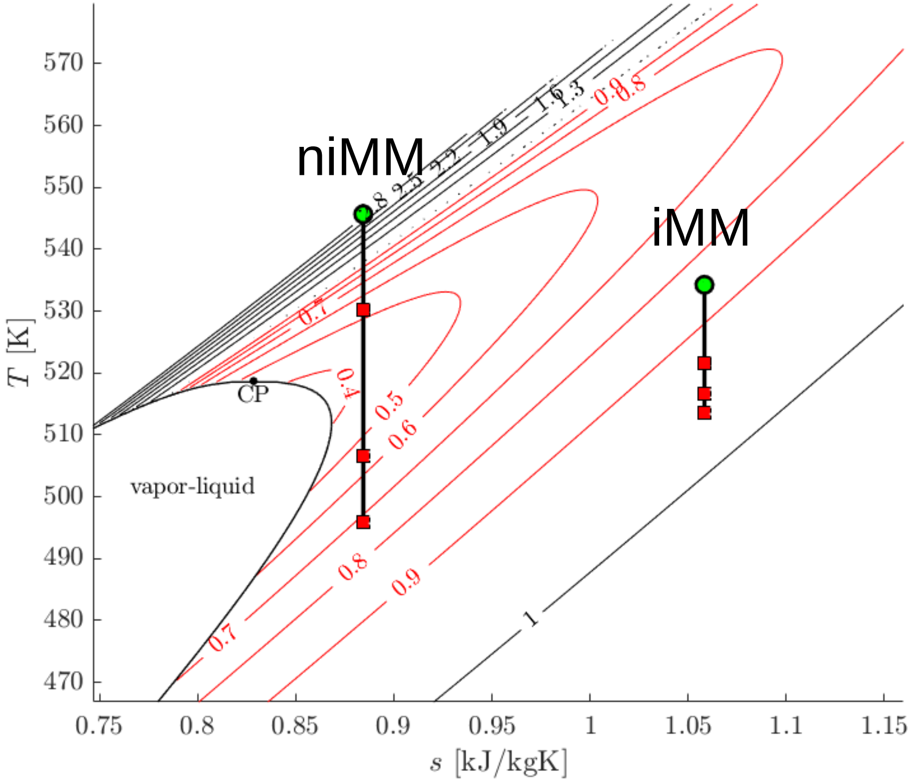
CFD Verification

Test Cases & Numerical Setting

3D transonic stator vanes

iMM: $\beta_{ts} = 2.0 - 2.8 - 3.4$
niMM: $\beta_{ts} = 1.8 - 2.7 - 3.8$

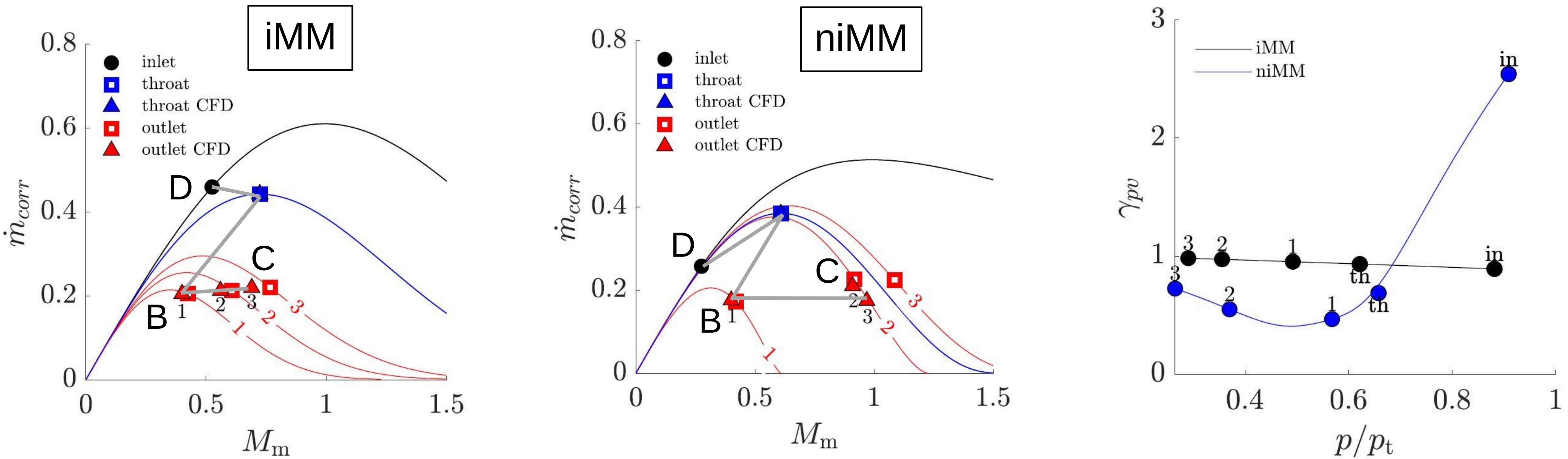
Spatial discretization: 2nd order
Turbulence: $k - \omega\ SST\ (y^+ \leq 1)$
Fluid mesh: 5M points
Look-up table: 2.5M (iMM) - 4M (niMM) points



Results

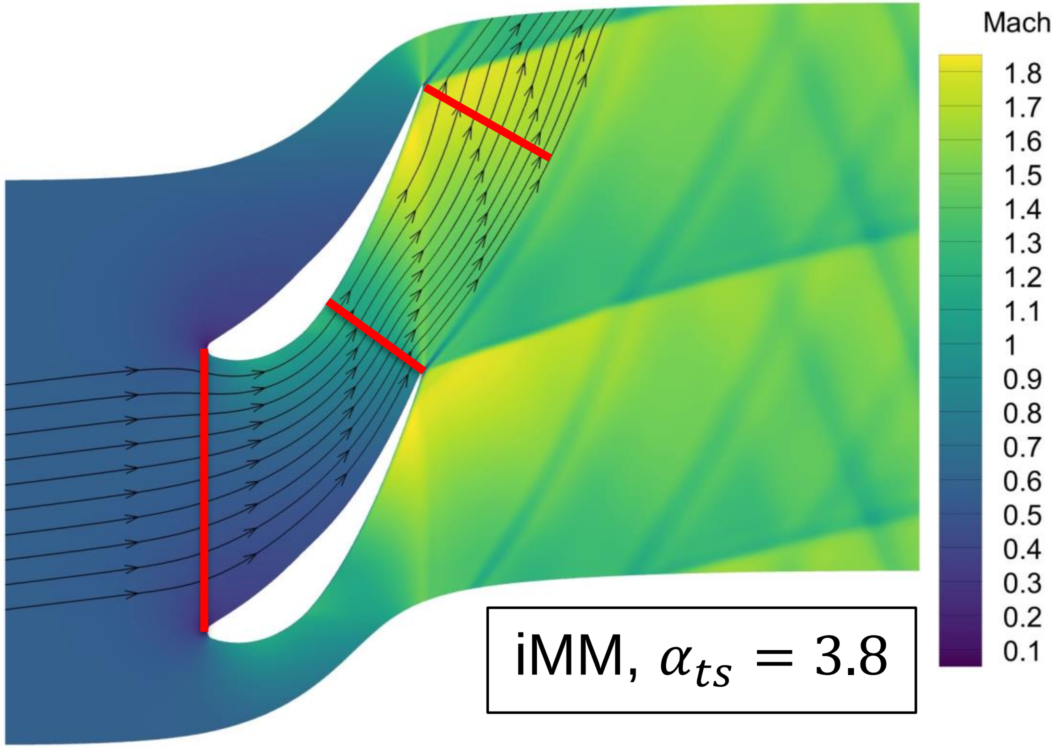
- 1D model qualitatively in line with CFD if sufficiently far from chocking

- Large deviation in volumetric flow ratio
  - iMM: $\alpha_{ts} = 2.2 - 3.1 - 3.8$
  - niMM: $\alpha_{ts} = 1.6 - 4.0 - 6.9$

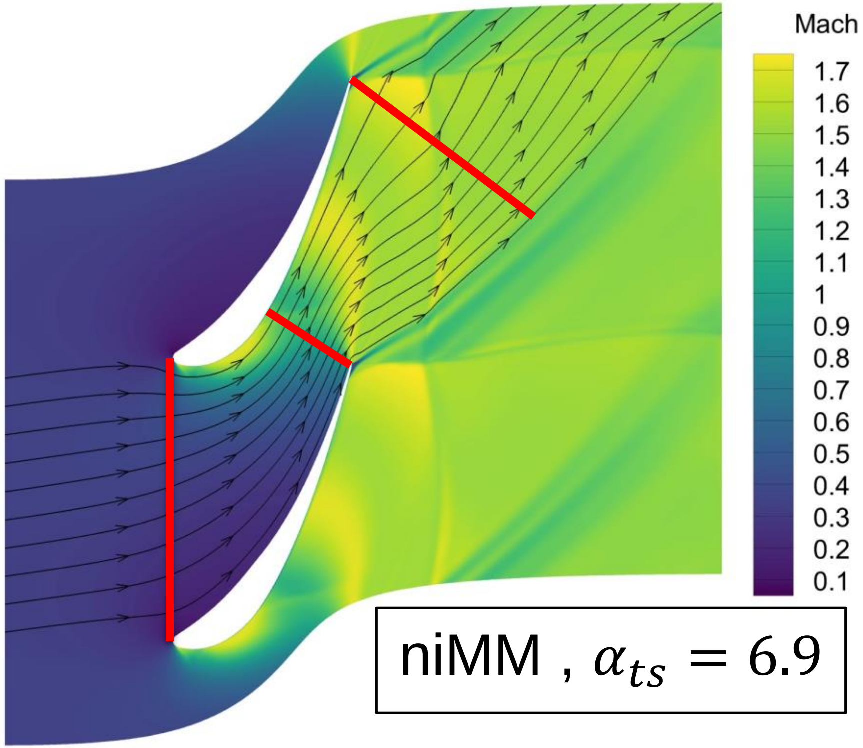


Physical Insights

- $\gamma_{pv} < \gamma$ $\rightarrow$ larger area variation to accommodate larger α at given β
- $\gamma_{pv} < \gamma$ $\rightarrow$ larger flow deviation in convergent blade channels



iMM, $\alpha_{ts} = 3.8$



niMM , $\alpha_{ts} = 6.9$

Take-Away Messages

- Expansions characterized by $\boldsymbol{\gamma_{pv}} < \boldsymbol{\gamma}$ lead to **earlier choking** and **larger flow deviation** when fixing β_{ts}

- Turbines operating with flow $\gamma_{pv} < \gamma$ (ORC) more susceptible to reach **complete choking** → operability/efficiency issues

- **Research hypothesis:**
  choice of **convergent-divergent** nozzle driven by ability to control flow deviation and extend operating range

Ongoing & Future Work

- Verify hypothesis by
  - Investigate expansion in convergent-divergent nozzles
- Pre-expansion at compressor inlet
- Analysis of compression processes

Further info upon request @
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