Stability Improvements of Pressure-Based Compressible Solver and Validation for Industrial Turbomachinery Applications

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Agenda

- Stability improvements of pressure-based compressible solver
- Unified solver for incompressible and compressible flow
- Formulation of energy equation
- Formulation and implementation of radial balance boundary condition
- Results for new tutorial
- Results for fan compressor (full-stage) and validation against NUMECA results

Steady-State Compressible Pressure-based Solver Review

- FOAM's steady-state pressure-based compressible solvers are not very stable
  - Especially for trans-sonic flows
  - Pressure and temperature waves are produced which are difficult to handle at boundaries
  - Reflections blow up the simulation
- Several solutions have been proposed, but the results has been lacking behind commercial competition

Derivation of pressure equation

Derivation of pressure equation in FOAM's compressible flow solvers:

1. Continuity Equation

$$\nabla\bullet(\rho\mathbf{U}) = 0$$

2. Substitute discretised Momentum Equation $A\mathbf{U} = H(\mathbf{U}) - \nabla p$

$$\nabla\bullet\left(\rho\frac{H(\mathbf{U})}{A}\right) = \nabla\bullet\left(\frac{\rho}{A}\nabla p\right)$$

3. Substitute discretised Momentum Equation $\rho = \frac{p}{RT} = \Psi p$

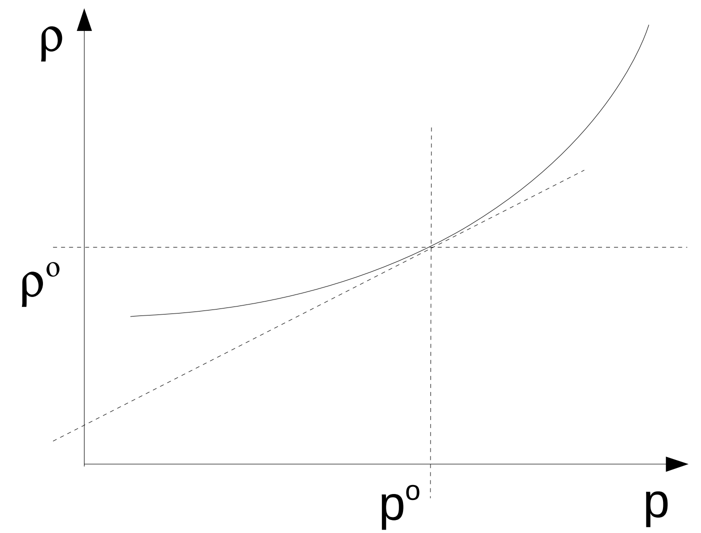
$$\nabla\bullet\left(\Psi\frac{H(\mathbf{U})}{A}p\right) = \nabla\bullet\left(\frac{\rho}{A}\nabla p\right)$$

Deficiencies of pressure equation

$$\nabla \bullet \left(\Psi \frac{H(\mathbf{U})}{A} p \right) = \nabla \bullet \left(\frac{\rho}{A} \nabla p \right)$$

- Derivation is formally correct, but ...
- Equation does not assume incompressible equation in the incompressible limit – $\Psi \rightarrow 0$ (?)
- Incompressible limit? You substituted the ideal gas law! What do you expect?
- Shouldn't we linearise around p^o

$$\rho = \rho^o + \frac{\partial \rho}{\partial p}\bigg|_{?} (p - p^o)$$



Derivation of new pressure equation

1. Continuity Equation
2. Substitute discretised Momentum Equation $A\mathbf{U} = H(\mathbf{U}) - \nabla p$

$$\nabla \bullet \left(\rho \frac{H(\mathbf{U})}{A} \right) = \nabla \bullet \left(\frac{\rho}{A} \nabla p \right)$$

3. Substitute linearisation $\rho = \rho^o + \left. \frac{\partial \rho}{\partial p} \right|_? (p - p^o)$

$$\nabla \bullet \left(\left. \frac{\partial \rho}{\partial p} \right|_? \frac{H(\mathbf{U})}{A} p \right) + \nabla \bullet \left(\left(\rho^o - \left. \frac{\partial \rho}{\partial p} \right|_? p^o \right) \frac{H(\mathbf{U})}{A} \right) = \nabla \bullet \frac{\rho}{A} \nabla p$$

- In the incompressible limit, the incompressible pressure equation is obtained → That's what we wanted!
- Which compressibility should we use?

Choice of compressibility

- Assume that enthapy is fixed during solution of the pressure equation

$$\left.\frac{\partial \rho}{\partial p}\right|_h = \left.\frac{\partial \rho}{\partial p}\right|_T = \frac{1}{RT}$$

- We had that and it does not work that well
- We notice that a change in pressure will change the enthalpy due to pressure work term

$$\nabla\bullet(\rho \mathbf{U} h) + \nabla\bullet\alpha_{eff}\nabla h = \tau\nabla\mathbf{U} + \nabla\bullet(\mathbf{U}p)$$

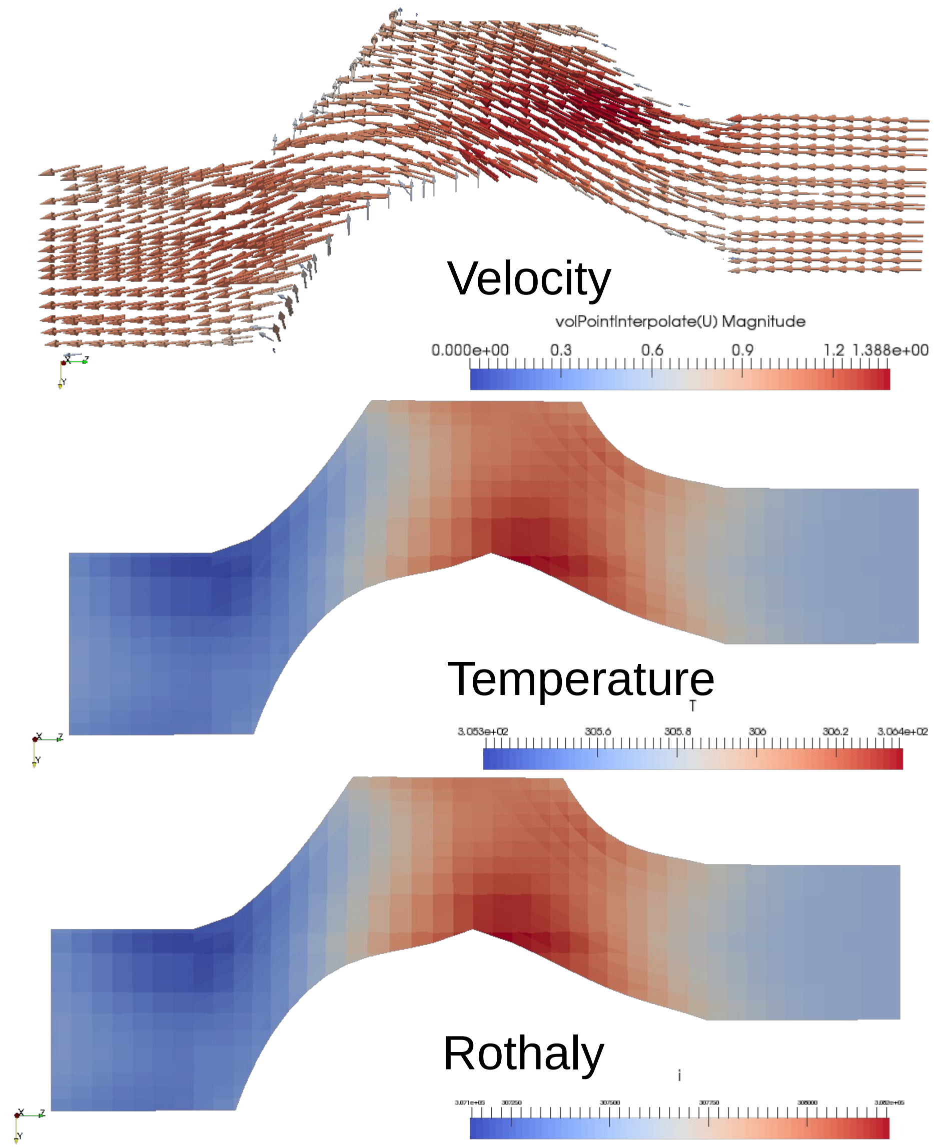
- Assume isentropic process instead

$$\left.\frac{\partial \rho}{\partial p}\right|_s = \frac{1}{\gamma RT}$$

- This works and drastically increases stability. Generalisations under-way.
- In fact, this is used in other major codes

Review of energy equations

- Implementation and validation of several formulations for the energy equation. In particular:
  - Rothalpy equation including jump conditions at moving frame boundaries (Ilaria Dedominicis, Alstom Power / GE)
  - Total energy equation including moving frame correction

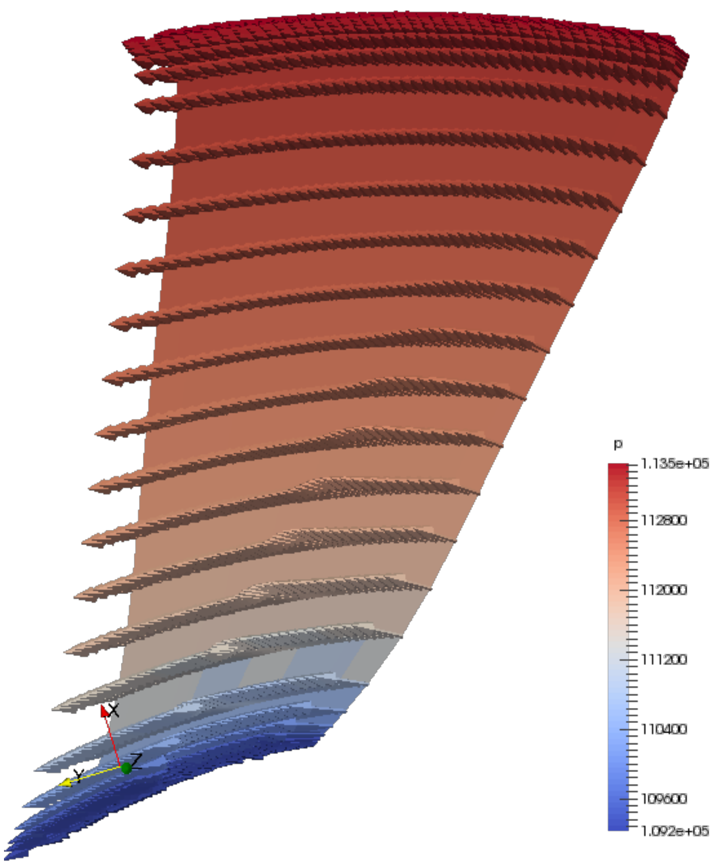


Radial Equilibrium Pressure Boundary Condition

- Implementation of radial equilibrium pressure boundary condition

$$\frac{\partial p}{\partial r} = \frac{\rho V_\Theta^2}{r}$$

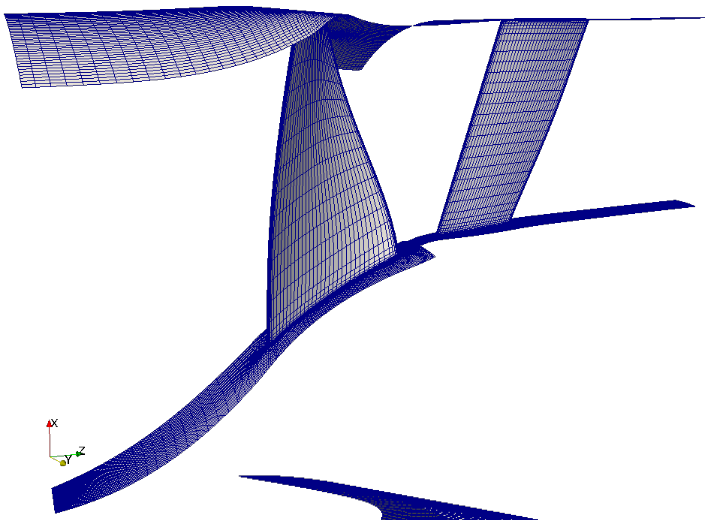
- Implementation requires integration along radius
- p_{ref} is either fixed or adjusted to match a given mass flow rate using a PID controller

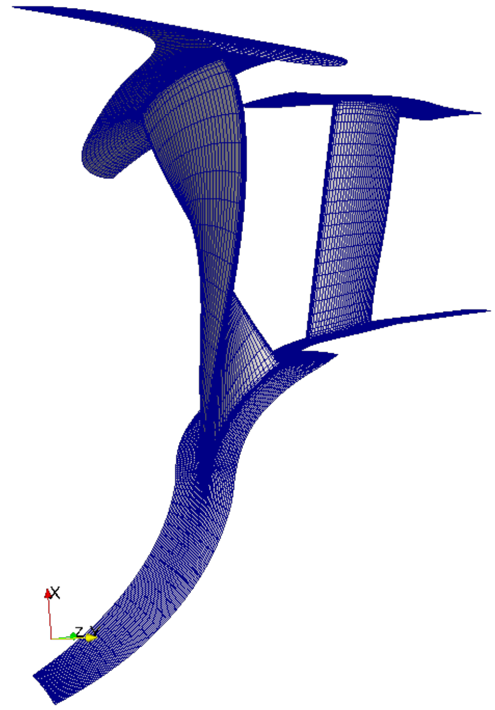


Validation for Fan Compressor

- Full stage (rotor-stator)
- Total energy equation
- @inlet:
  Total pressure, Total temperature
- @oulet:
  Radial equilibrium pressure boundary condition with p_{ref} adjusted to match specified mass flow rate
  zeroGradient on temperature
- Mixing plane at interface

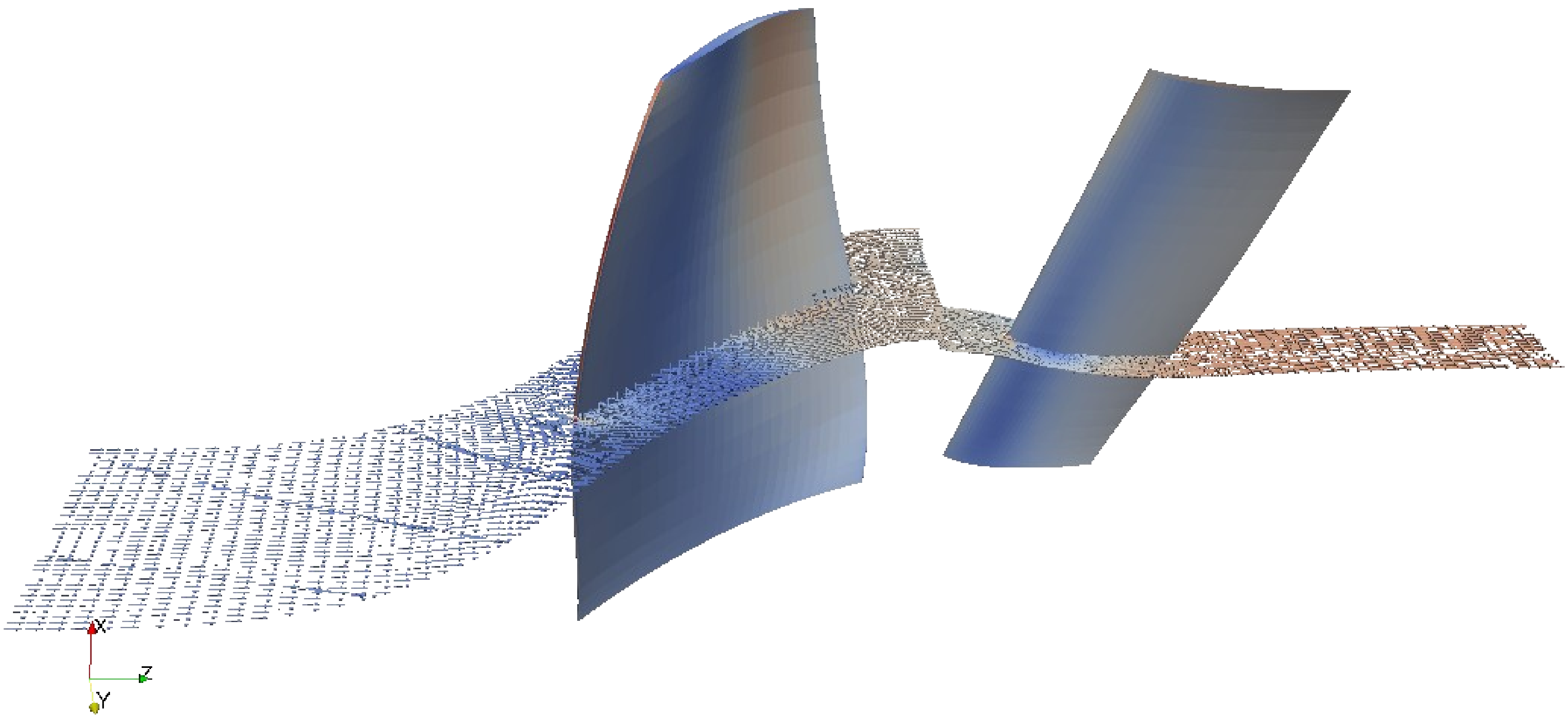
- 2 two RPMs
- More than 10 flow rates per RPM
- Results compared to NUMECA



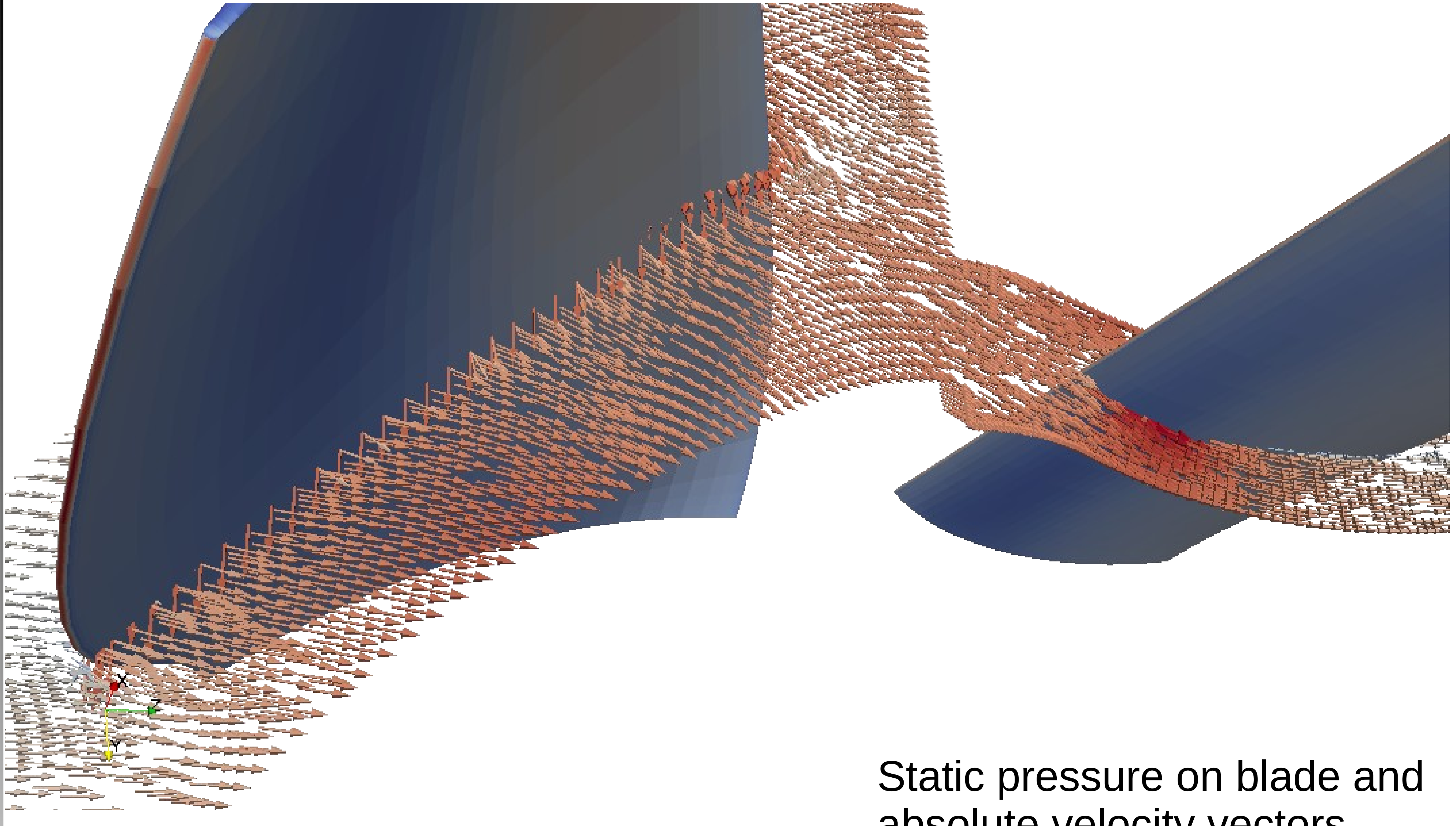


Representative Results

Static pressure on blade and
absolute velocity vectors

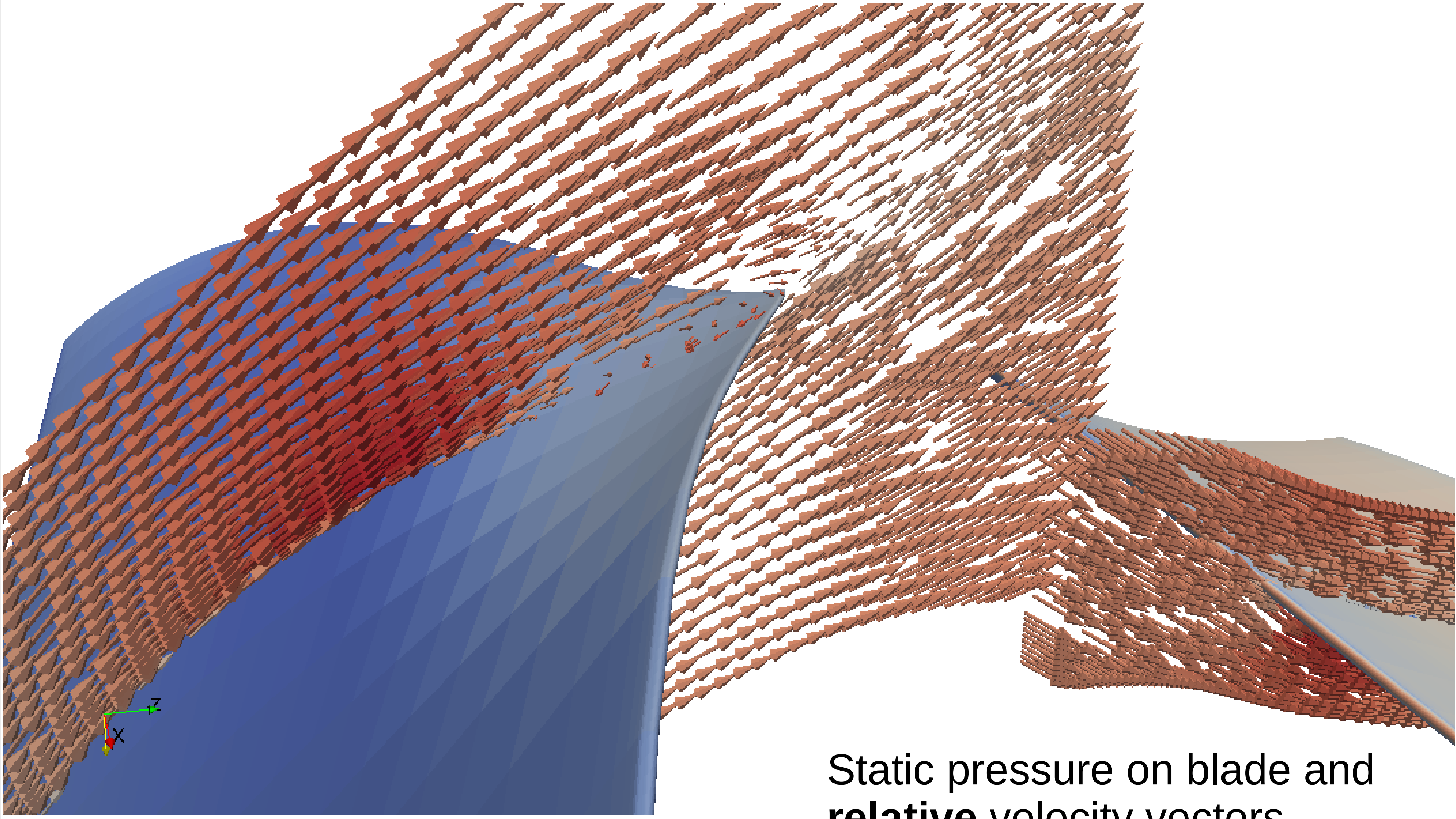


Representative Results



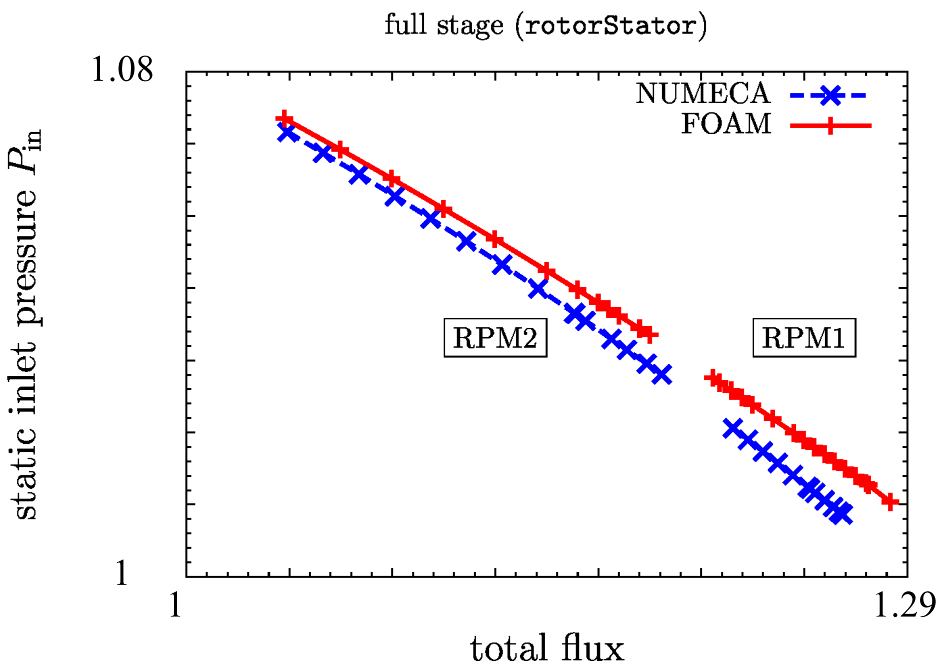
Static pressure on blade and absolute velocity vectors

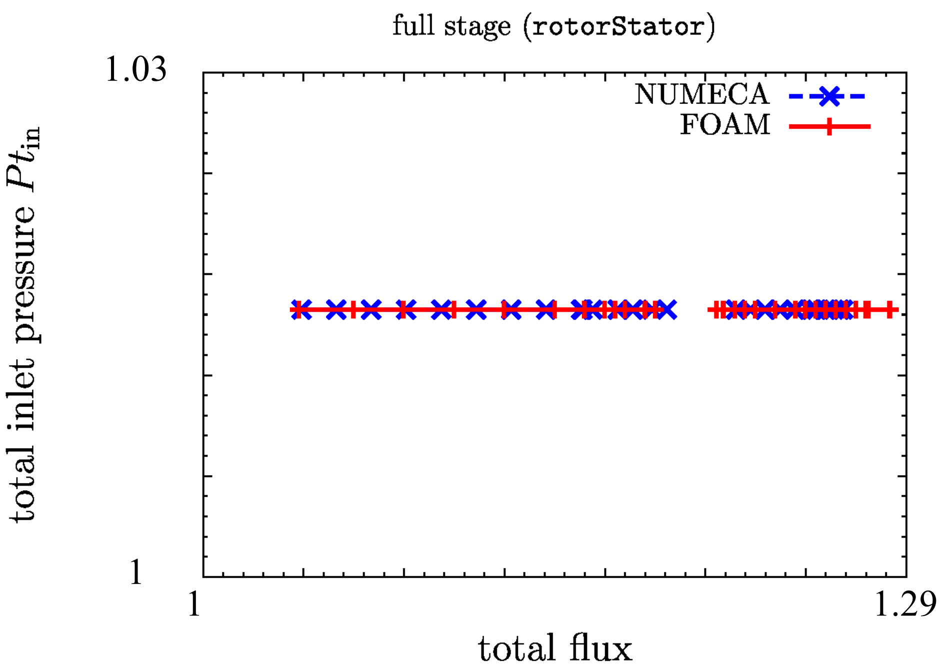
Representative Results



Static pressure on blade and **relative** velocity vectors

Compressor Maps





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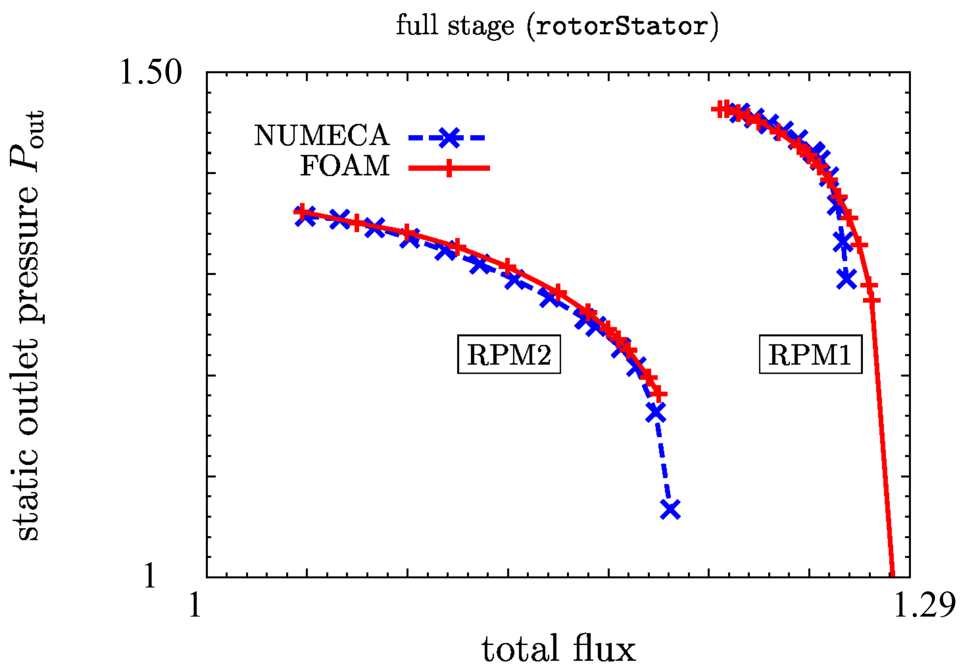

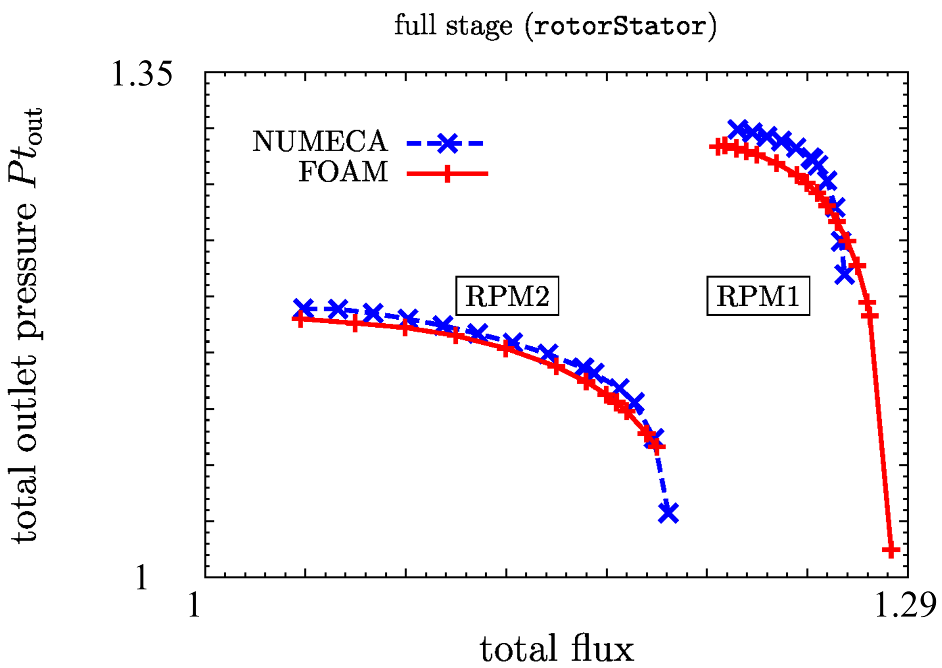

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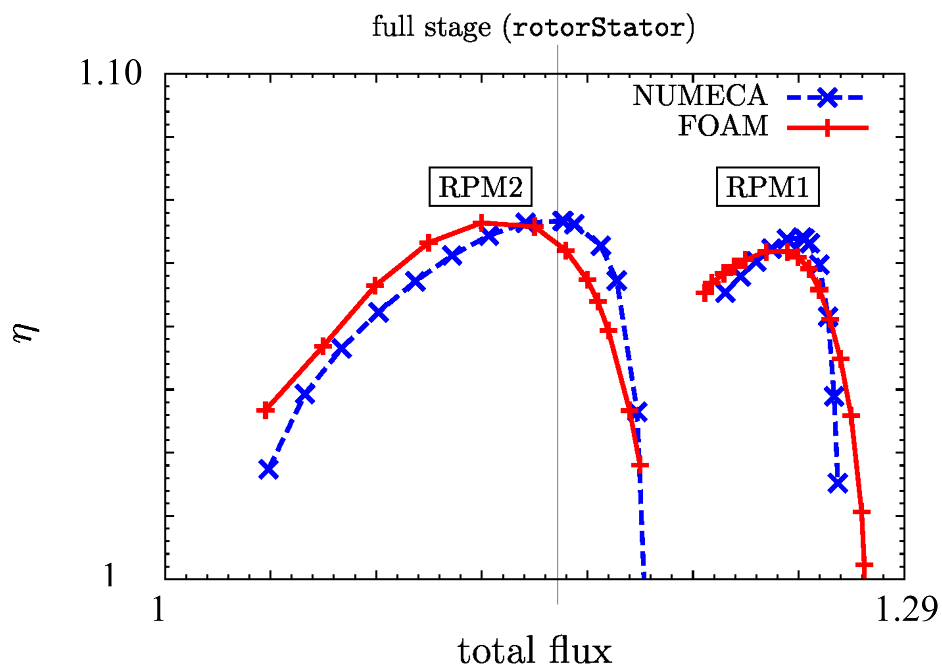
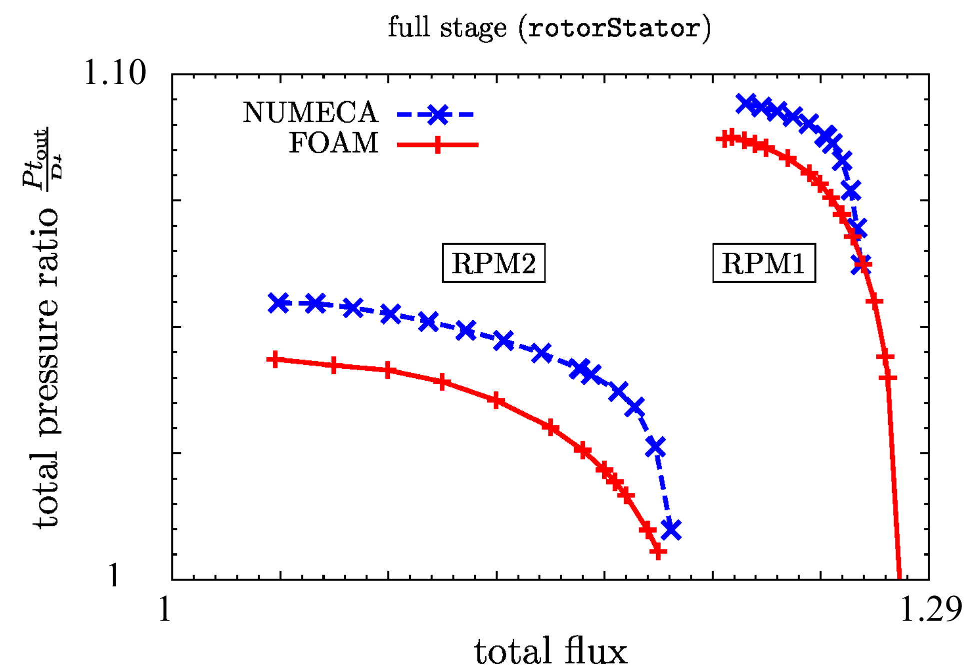
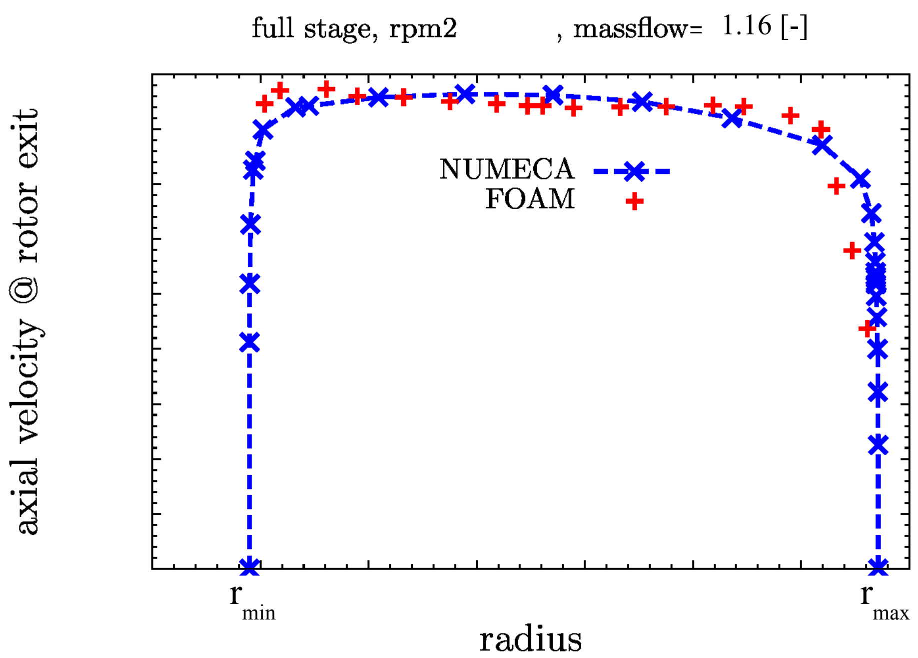
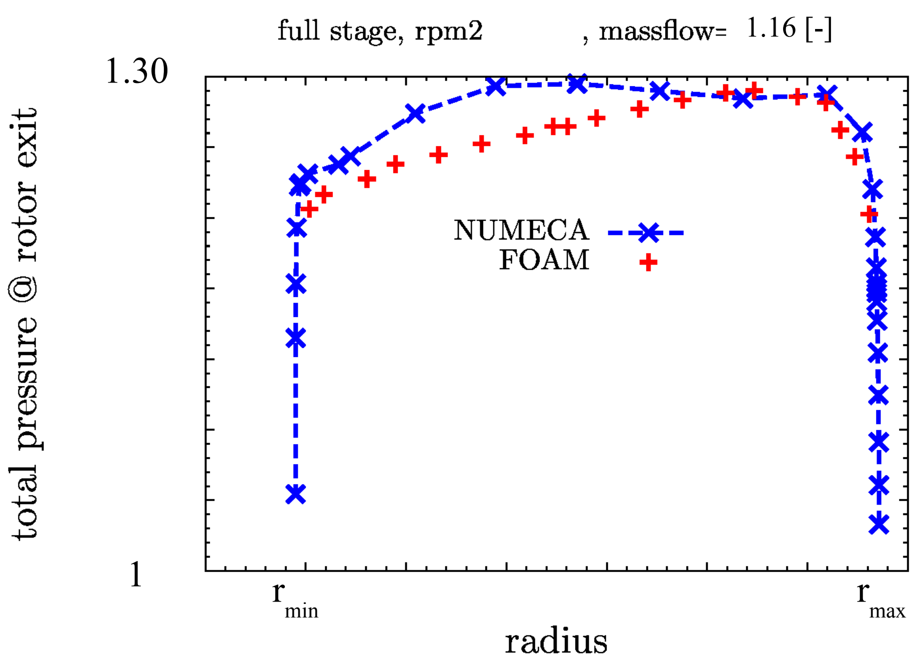




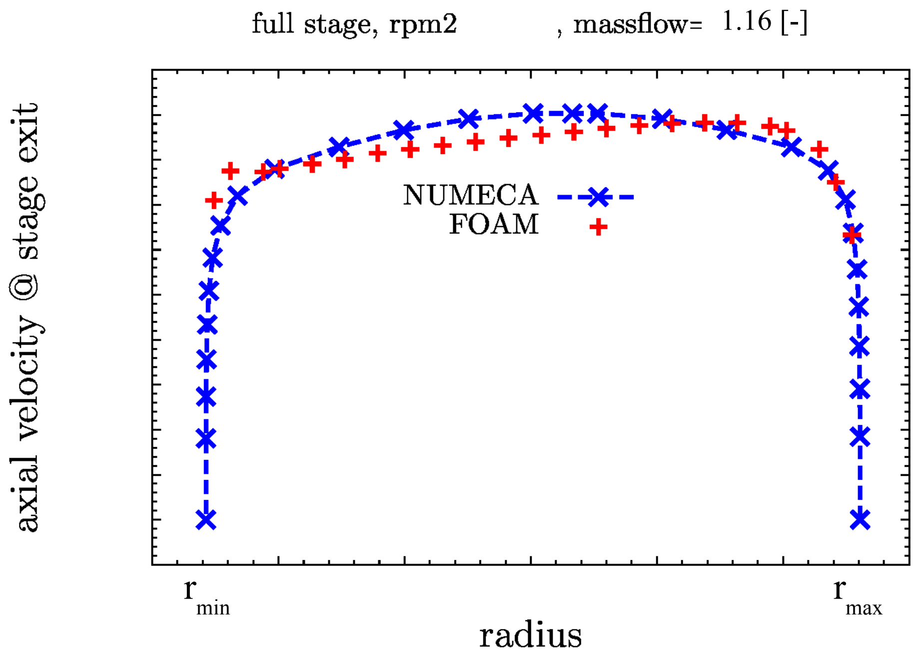
$$\eta_s = \frac{\left(\frac{\bar{p}_{tot,i}}{\bar{p}_{tot,o}}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\frac{\bar{T}_{tot,i}}{\bar{T}_{tot,o}} - 1}$$

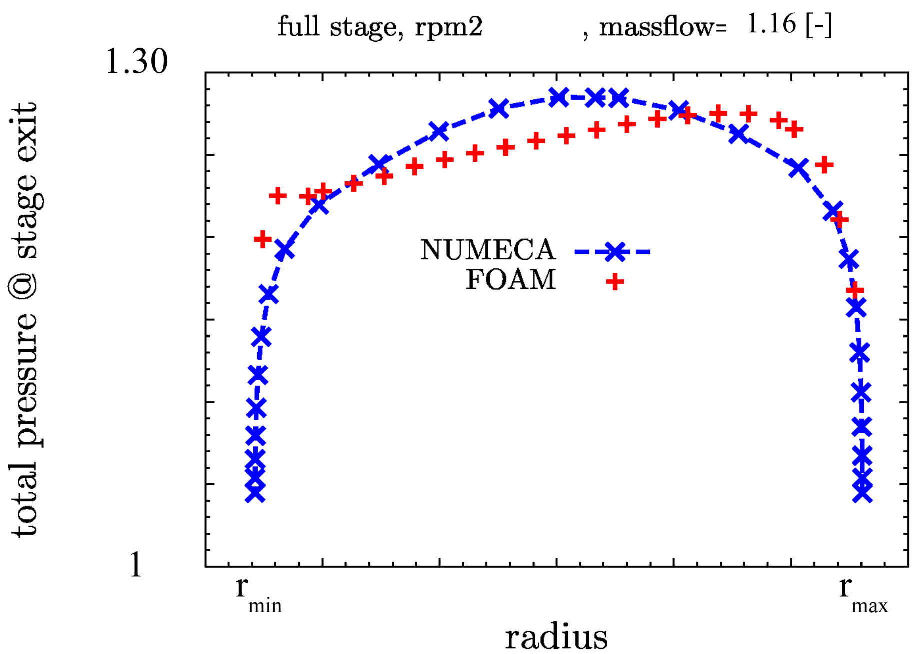
Span-wise distributions @ rotor exit for RPM2





Span-wise distributions @ stage exit for RPM2





Conclusions and Future Work

- Stability of compressible solver increased substantially
- Unified solver released
- Implemented many features critical for turbo-machinery applications
- Initial validation results are encouraging
- Differences are being investigated

Thank you for your attention!

Questions?