DEVELOPMENT OF A SPACE MARCHING THROUGHFLOW CODE FOR RADIAL INFLOW TURBINES

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Aim:

Develop a space marching 1D throughflow code for radial turbomachinery

Introduction:

- Organic Rankine cycles and supercritical CO2 Brayton cycles have received increased attention due to their ability to efficiently extract energy from sources with a large range of temperatures.
- To make these cycles viable, it is necessary to concurrently optimise turbine geometry and cycle design for each application.
- Radial inflow turbines for these applications are typically designed using 1D mean-line solvers prior to full 3D CFD.
- Current preliminary methods (mean-line solvers) do not offer insights into flow field internal to the rotor, whilst CFD is not fast enough for design space exploration studies
- Throughflow codes are a means to fill this gap. This poster describes the development of TOPTURB, a solver for radial inflow turbines.
- As an enhancement to mean-line codes, TOPTURB includes rotor passage and area schedule definition. It calculates losses based on the local passage geometry and flow properties to capture more aspects of the flow physics. At the same time, computational time remains low enabling design space exploration and automated optimisation.

Theory and Methods:

Geometry definition

- Rotor geometry (passage shape) is defined as a meridional streamline (parametric curve) and area schedule between inlet and outlet [1].
- Fluid flow treated as a rotating 1-D duct flow under consideration of:
  - Out of plane body forces due to rotation and path
  - Area change along passage
  - Change in enthalpy (losses and work extraction)
  - Frictional forces in the streamwise direction
- 3D rotating duct represented in Fig. 1, reduced to 1D in Fig. 2.

Flow solution

- Set of governing equations adapted from Shapiro [2] solved in relative reference frame using a forward difference space marching scheme
- Losses can be accounted for by:
  1. Uniformly distributed enthalpy loss using values from established solvers
  2. Friction factors based on local geometry and flow properties
  3. Prescribed entropy distributions

Post processing

- Performance parameters, blade loadings and net force distributions along the rotor passage are extracted from the flow-field solution.

Comparison case

- Rotor and flow conditions for air turbine presented in Sauret [3] used as a test case

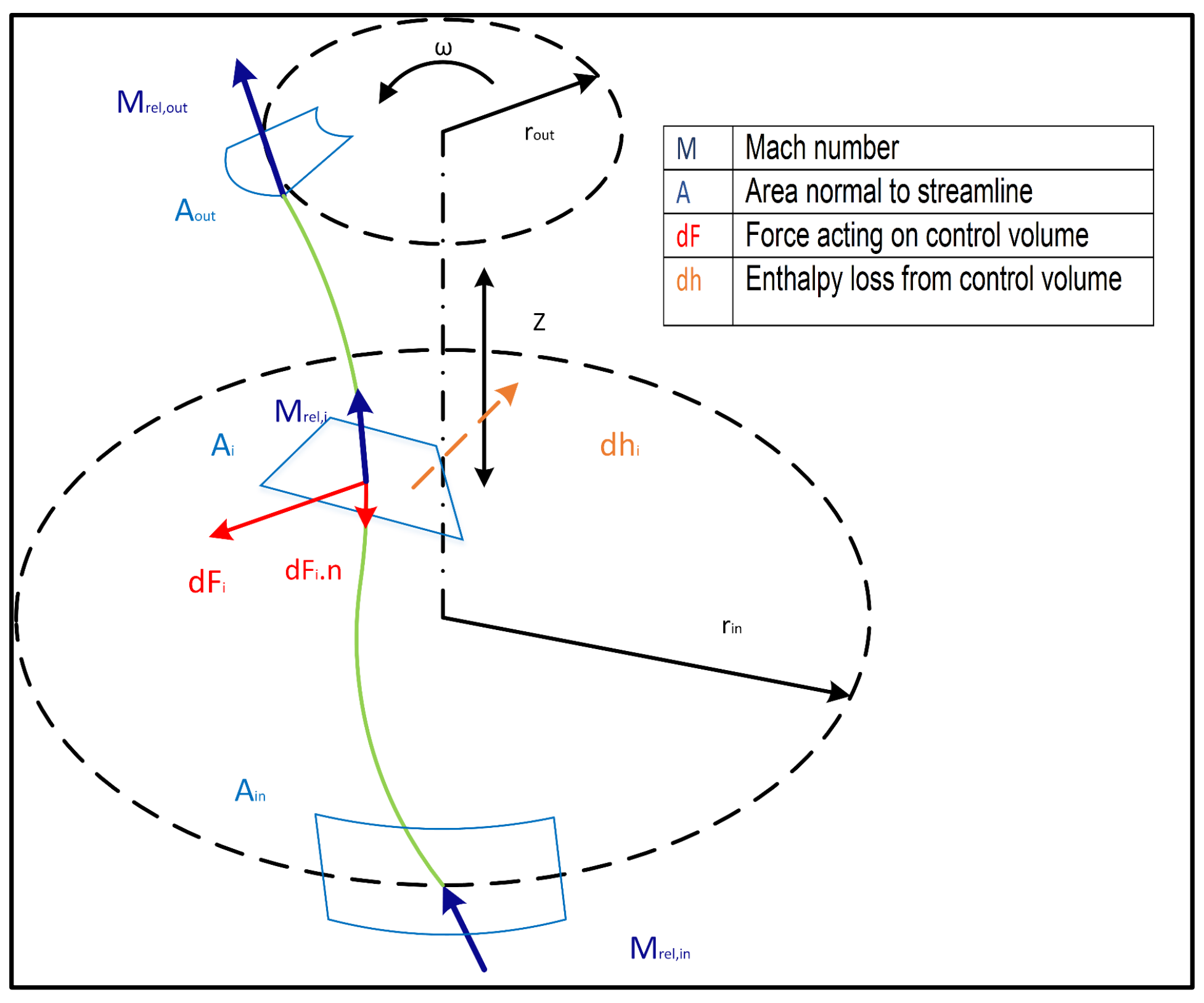

Figure1: Schematic of rotor geometry for TOPTURB

Governing Equations

$$\frac{d(M^2)}{M^2} = \frac{-2(1+\frac{\gamma-1}{2}M^2)}{1-M^2}\frac{dA}{A} + \frac{(1-\gamma M^2)}{1-M^2}\frac{dh}{C_pT} + \frac{(1+\frac{\gamma-1}{2}M^2)}{1-M^2}\frac{dF}{\frac{1}{2}\gamma PAM^2} \quad (1)$$

$$\frac{dT}{T} = \frac{(\gamma-1)M^2}{1-M^2}\frac{dA}{A} + \frac{(1-\gamma M^2)}{1-M^2}\frac{dh}{C_pT} - \frac{\gamma(\gamma-1)M^4}{2(1-M^2)}\frac{dF}{\frac{1}{2}\gamma PAM^2} \quad (2)$$

$$\frac{d\rho}{\rho} = \frac{M^2}{1-M^2}\frac{dA}{A} - \frac{1}{1-M^2}\frac{dh}{C_pT} - \frac{\gamma M^2}{2(1-M^2)}\frac{dF}{\frac{1}{2}\gamma PAM^2} \quad (3)$$

$$\frac{dP}{P} = \frac{\gamma M^2}{1-M^2}\frac{dA}{A} - \frac{\gamma M^2}{1-M^2}\frac{dh}{C_pT} - \frac{\gamma M^2(1+(\gamma-1)M^2)}{2(1-M^2)}\frac{dF}{\frac{1}{2}\gamma PAM^2} \quad (4)$$

$$\frac{ds}{C_p} = \frac{dh}{C_pT} + \frac{(\gamma-1)M^2}{2}\frac{dF}{\frac{1}{2}\gamma PAM^2} \quad (5)$$

With dh and DF defined a

$$dF = d\vec{F}_{centrifugal} + d\vec{F}_{corriolis} \quad (6)$$

$$dh = \frac{\omega^2 d(r^2)}{2} + dh_{loss} \quad (7)$$

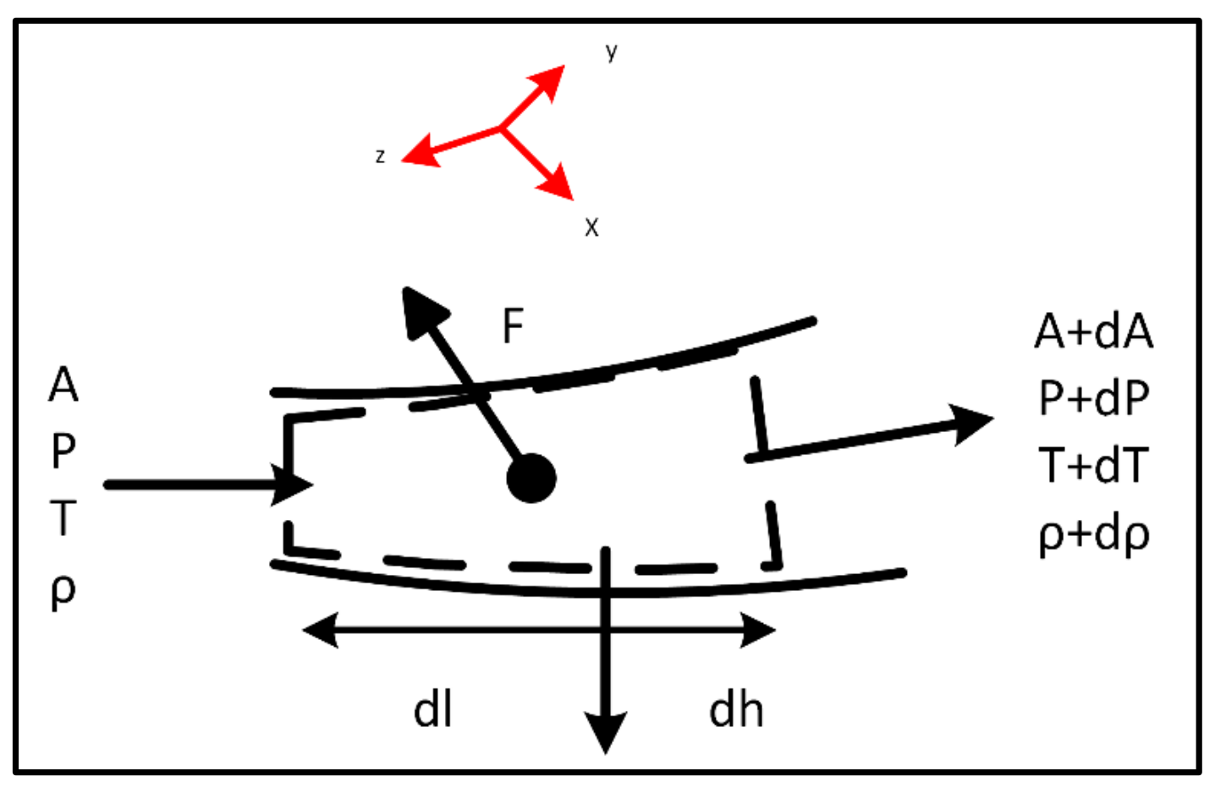

Figure 2: Control volume for duct flow in TOPTURB

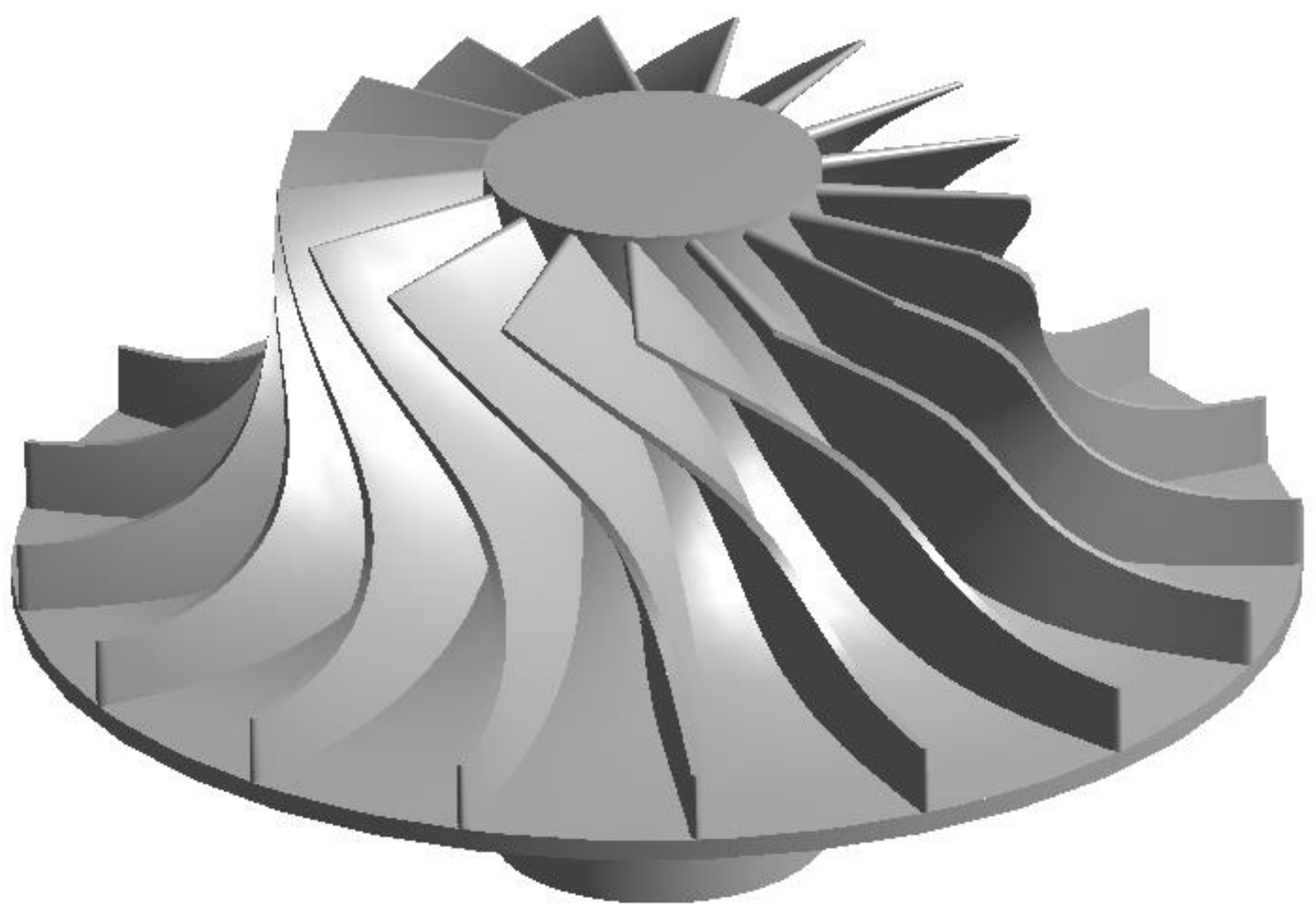

Figure 3: CAD model of rotor as used for analysis in Odabaee et.al. [4]

Rotor inlet conditions

$M_{abs\ in}$	0.95
T0	477.6K
P0	413.6 kPa
Shaft speed	71700 rpm

Rotor geometry

R_{in}	58.9mm
R_{out}	27.0mm
Z	34.2mm
A_{in}	$2.3\text{x}10^{-3}$ m^2
A_{out}	$5.6\text{x}10^{-3}$ m^2

Results:

CFD resolves initial flow turning, which is modelled as point momentum exchange in TOPTURB (see Fig. 5)

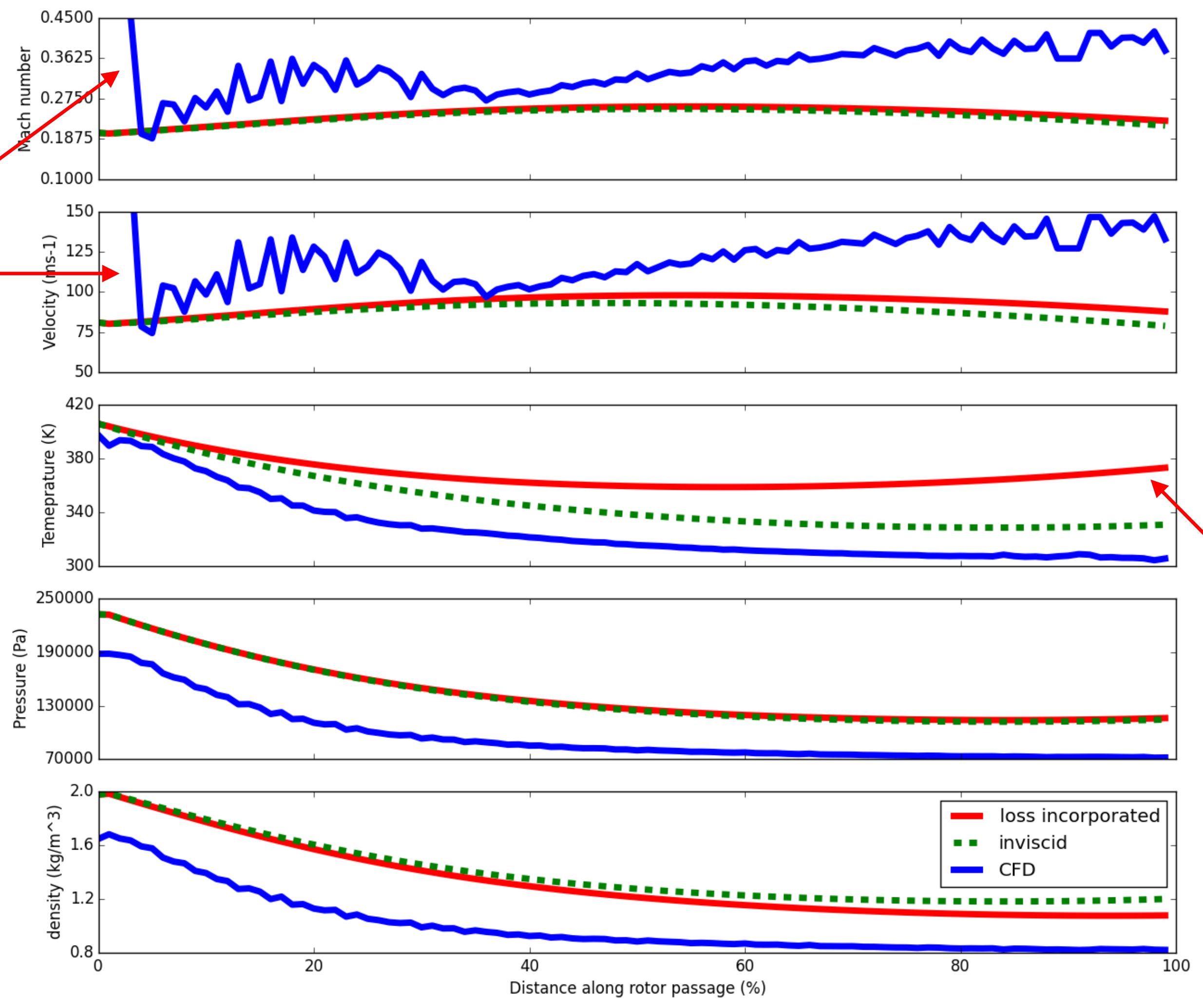

Figure 4: Properties along rotor tract solved with TOPTURB and mean properties solved with CFD solver CFX (adapted from simulations presented in [4]). TOPTURB losses accounted for using established mean-line loss models

Impulse due to flow turning at rotor inlet

Viscous Losses increase conversion of K.E to static enthalpy

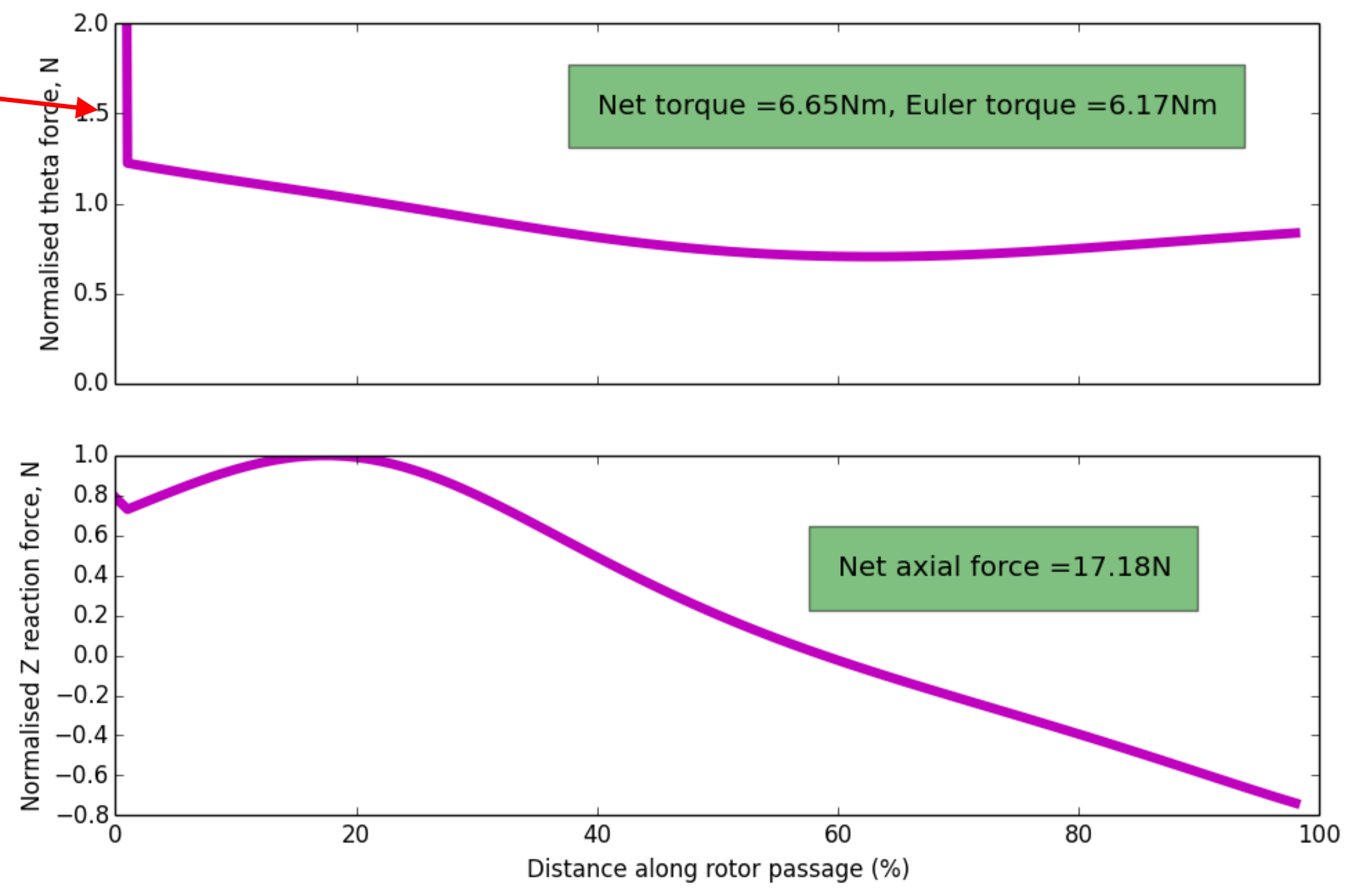

Figure 5: Normalised blade and axial forces solved with TOPTURB

Conclusion and Discussion:

- Trends in pressure, density and temperature are well matched between TOPTURB and CFX
- Net torque from control volume approach is a close match to Euler torque for rotor
- Control volume approach for passage forces can be used as a preliminary analysis tool for predicting blade loadings in the case of high density fluids
- TOPTURB under-predicts the speed and Mach number increase within the rotor passage. Differences are attributed to quality of loss models currently employed. Future work will investigate loss mechanisms that achieve better matching.
- TOPTURB solved in under 10 seconds on desktop PC compared with approximately 40 minutes for the nominal CFD case simulated by Odabaee et. Al. [4]

Acknowledgements

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References

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[2] Shapiro, A.H., 1953. The dynamics and thermodynamics of compressible fluid flow. *New York: Ronald Press, 1953-54, 1.*

[3] Sauret, E., 2012. Open design of high pressure ratio radial-inflow turbine for academic validation. *ASME Paper No. IMECE2012-88315.*

[4] Odabaee, M., Shanechi, M.M. and Hooman, K., 2014. CFD simulation and FE analysis of a high pressure ratio radial inflow turbine. *In 19AFMC: 19th Australasian Fluid Mechanics Conference (pp. 1-4).* Australasian Fluid Mechanics Society.