Analysis and modeling of the tip leakage vortex of an axial fan

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- **Low-speed** fan configuration USI7 $Re = 210,000$
- Influence of **tip clearance** and **operating condition**
- Evaluation of **losses** associated to **tip gap flow**

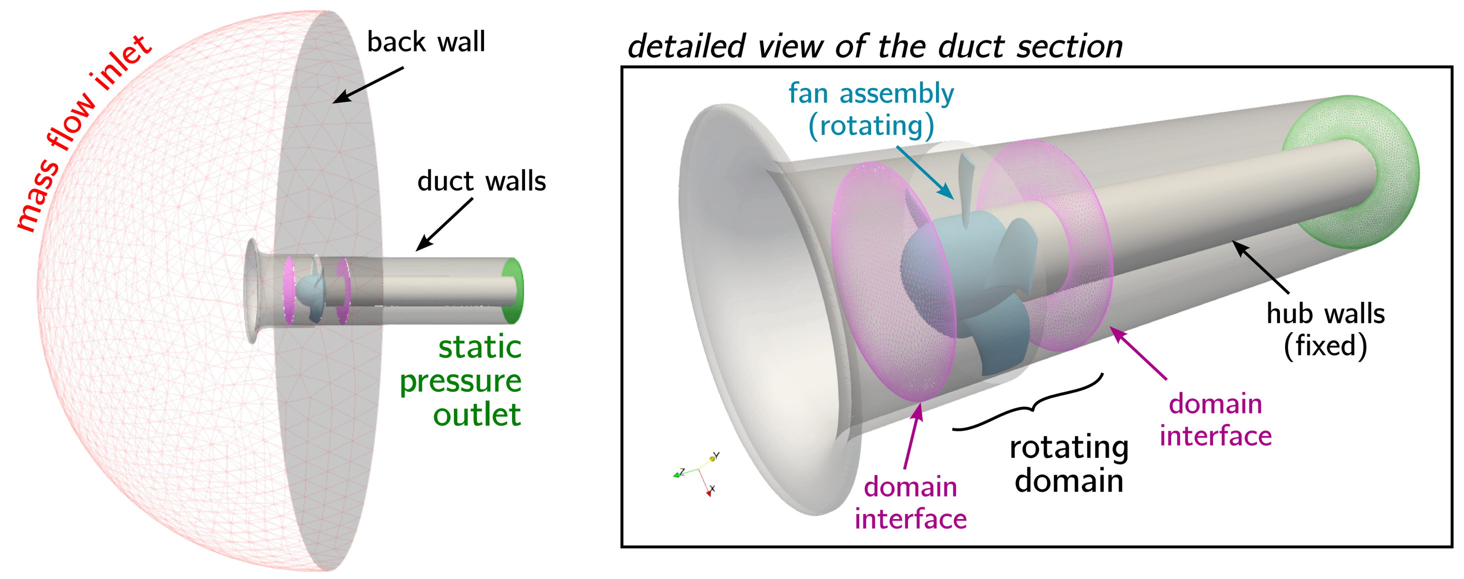
This study employs a RANS database of the USI7 configuration to assess a model [1] for predicting the losses associated with tip gap flow.

Numerical database

The numerical configuration shown below mimics the USI7 fan installed in a long circular duct, as it has been experimentally tested at the University of Siegen [2].

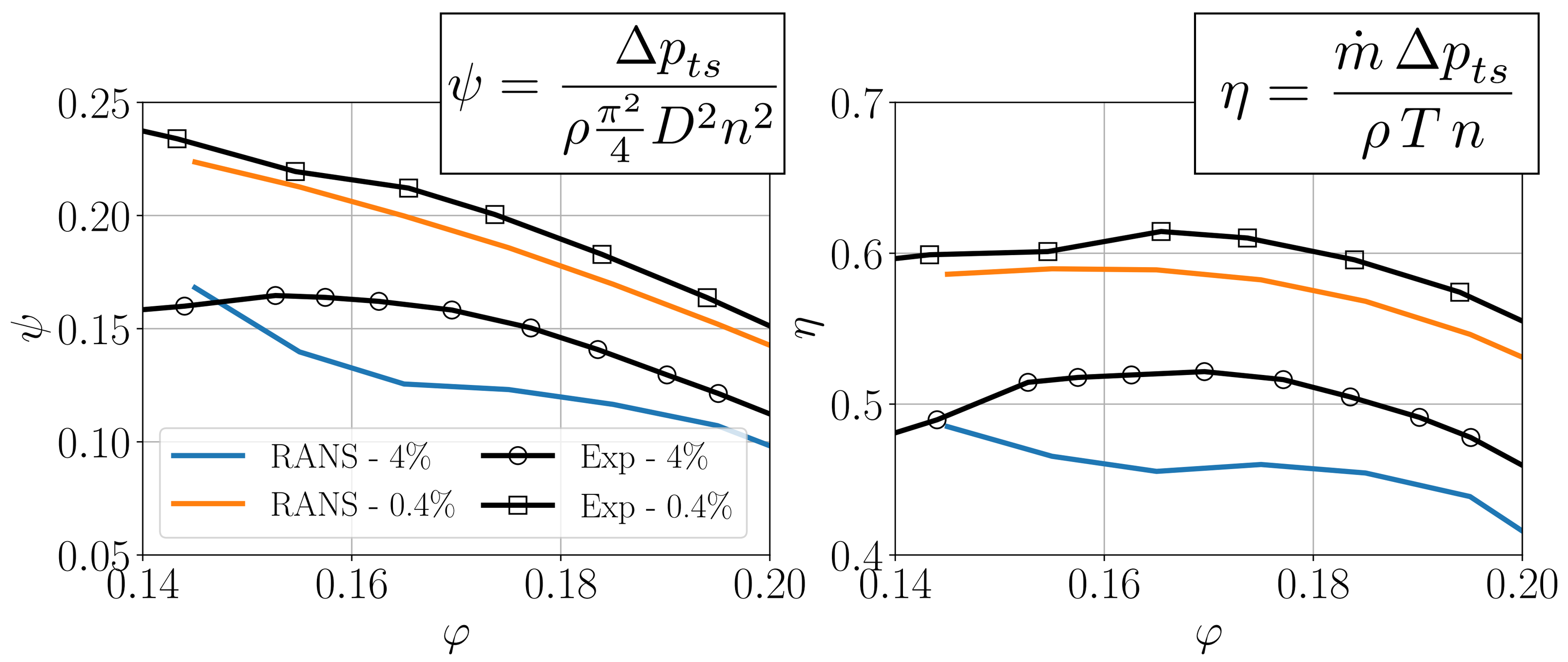
- **RANS**: ANSYS CFX, $k-\omega$ SST, incompressible
- **Tip-clearance**: $\tau/c = 0.4\%, 4\%$
- **Flow coefficient** $\varphi \in [0.145, 0.195]$

$$\varphi = \frac{\dot m}{\rho \frac{\pi^2}{4} D^3 n}$$



Both experiments [2] and simulations show a **reduction in efficiency by 10% with the increased tip clearance**. RANS modeling limitations explain discrepancies.

$$\psi = \frac{\Delta p_{ts}}{\rho \frac{\pi^2}{4} D^2 n^2} \qquad \eta = \frac{\dot m\, \Delta p_{ts}}{\rho\, T\, n}$$



Loss analysis

The numerical database is used to quantify the losses ζ. Two 2 approaches are used:

1. Stagnation pressure loss across the rotating domain
2. Volume integration of entropy production rate

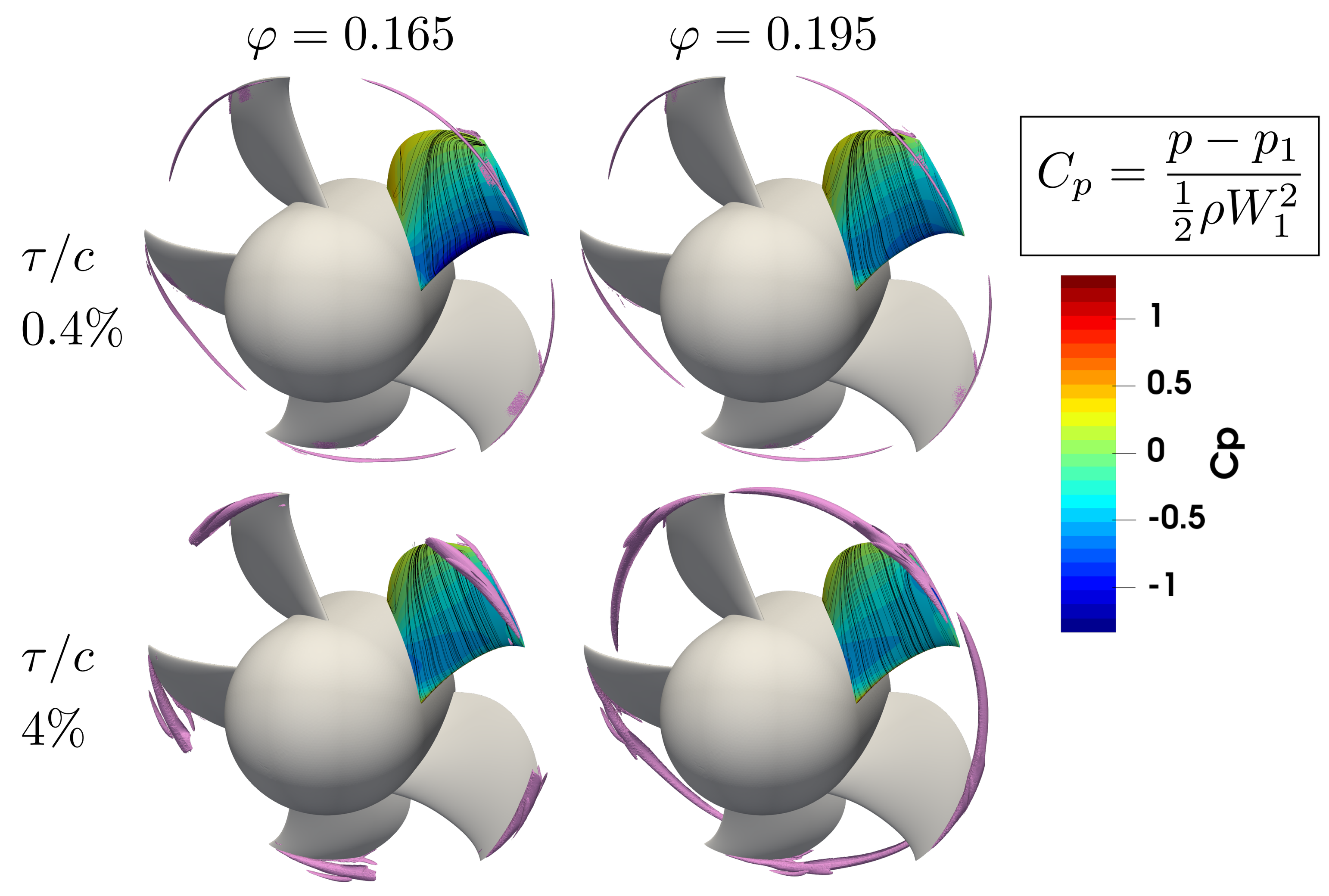
The former provides better precision, the latter allows quantifying the contribution of various flow features.

- $\tau/c = 0.4\%$: boundary layer associated losses are the major contribution, tip flow losses contribute up to 20% to total losses at low flow coefficient.
- $\tau/c = 4\%$: **tip flow losses contribute for more than 50%** of total losses at all flow coefficients.

Tip leakage vortex

The tip gap flow is dominated by the tip leakage vortex identified by the pink iso-surface of Q criterion. Its relative **position** to the blade and its **strength** vary with φ and τ/c. It affects the blade loading as can be seen by C_p contours and streaklines.

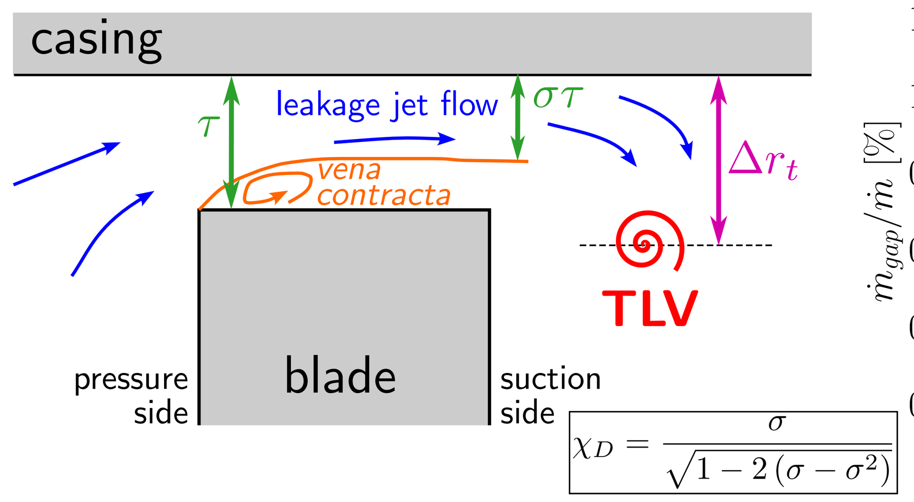
$$C_p = \frac{p - p_1}{\frac{1}{2}\rho W_1^2}$$

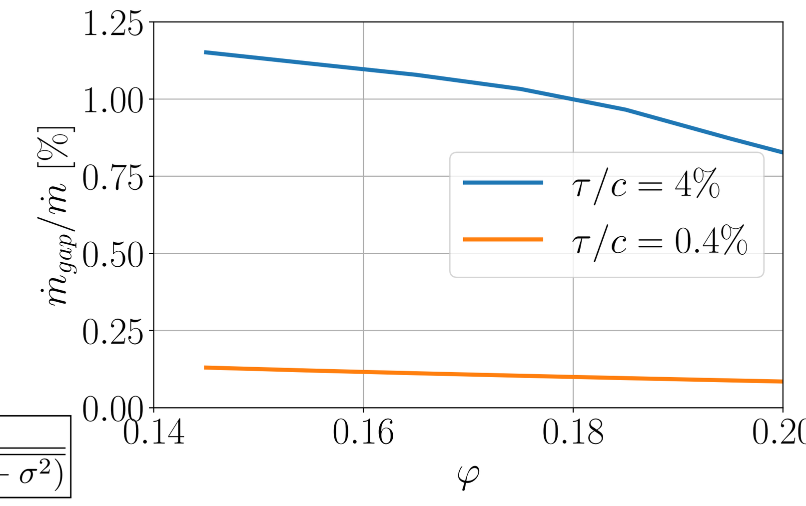


Assumption 1 – The tip gap flow losses ζ_t are proportional to the square of the tip leakage vortex strength Γ.

The tip leakage vortex is fed by the leakage flow through the gap. The momentum of the leakage jet flow can be related to the blade loading C_L and the discharge coeficient χ_D. The later can be quantified by a thorough analysis of *vena contracta* effect through the clearance [3].

$$\chi_D = \frac{\sigma}{\sqrt{1 - 2(\sigma - \sigma^2)}}$$





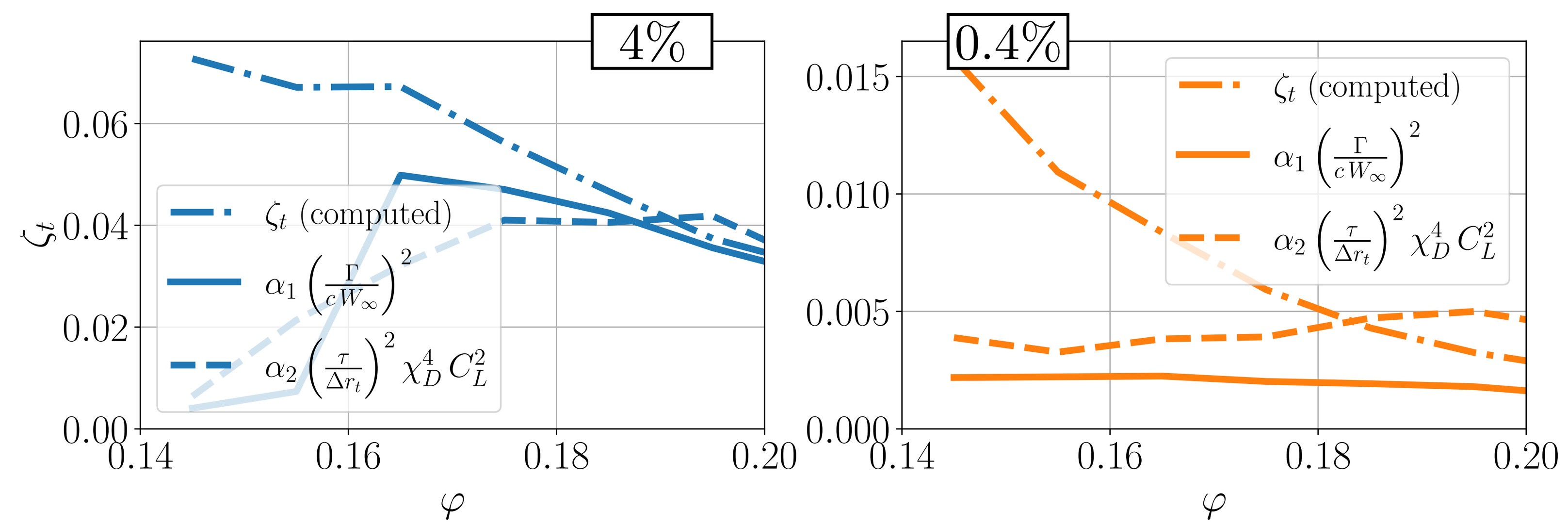
Assumption 2 – The tip leakage vortex strength Γ is proportional to leakage jet flow momentum $\chi_D \dot m_{\text{gap}} W_\infty$.

Modeling of tip flow losses

Based on the two assumptions, Deveaux's model [1] yields the following expression:

$$\zeta_t = \alpha_1 \left(\frac{\Gamma}{cW_\infty}\right)^2 = \alpha_2 \left(\frac{\tau}{\Delta r_t}\right)^2 \chi_D^4 C_L^2$$

The model developed for isolated airfoil configuration has been evaluated in a rectilinear cascade configuration [4]. The assumptions are evaluated with the USI7 RANS database. The trends are good at high flow coefficients, but calibration coefficients α_1, α_2 will be required.



References

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