The Impact of Airfoil Leading Edge Shape on Erosion Rate

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Motivation

- Leading Edge Erosion (LEE) is a major mechanism causing WT performance degradation, with growing significance in the future
- Mitigation approaches mainly focus on protective techniques
- Relevant parameters for particle erosion are identified

- Can an airfoil design approach help reduce potential erosion?

- Particularly, how does changing the LE radius effect erosion metrics?

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Method

- Analysis for $Re = 12 \cdot 10^6\ ,\ \mathrm{AoA} = 8°$
- FFA-W3-3211 + 3 airfoil modifications with different LE radii (isolated)

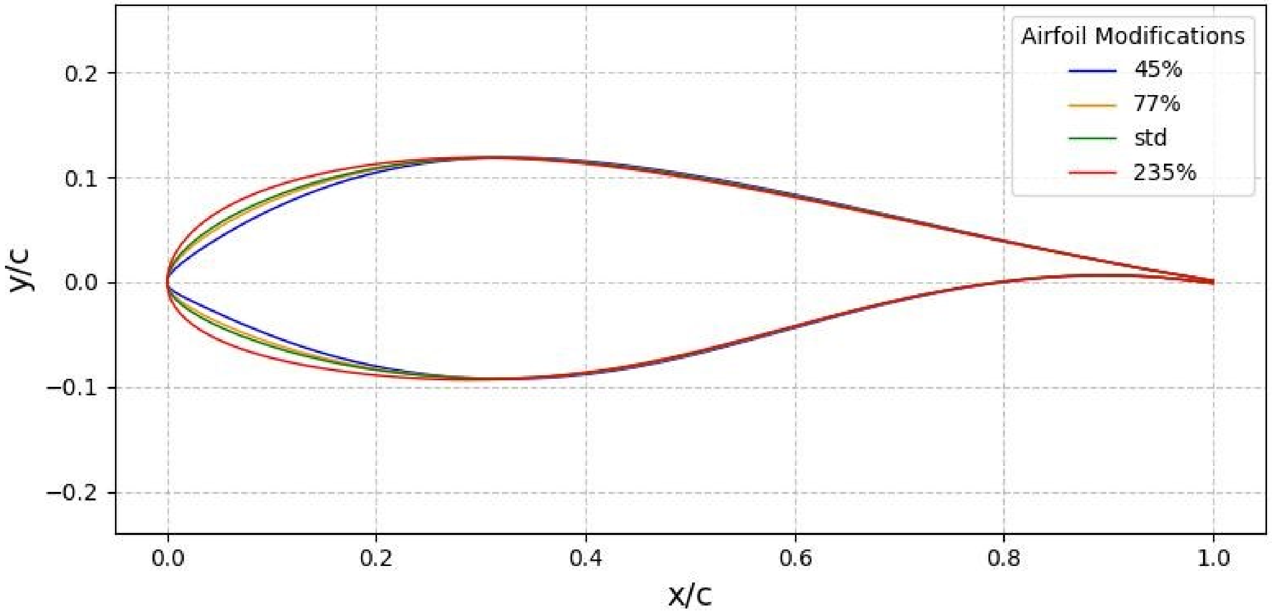

Fig. 1: FFA-W3-3211 airfoil (std) and LE radius modifications

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Method

- CFD 2-stage (Eulerian-Lagrangian) multiphase analysis in OpenFOAM [1]
  - steady-state RANS solver (SST k – ω turbulence model) for background flow field
  - 1-way coupled Lagrangian Particle Tracking (LPT) solver for erosion metrics

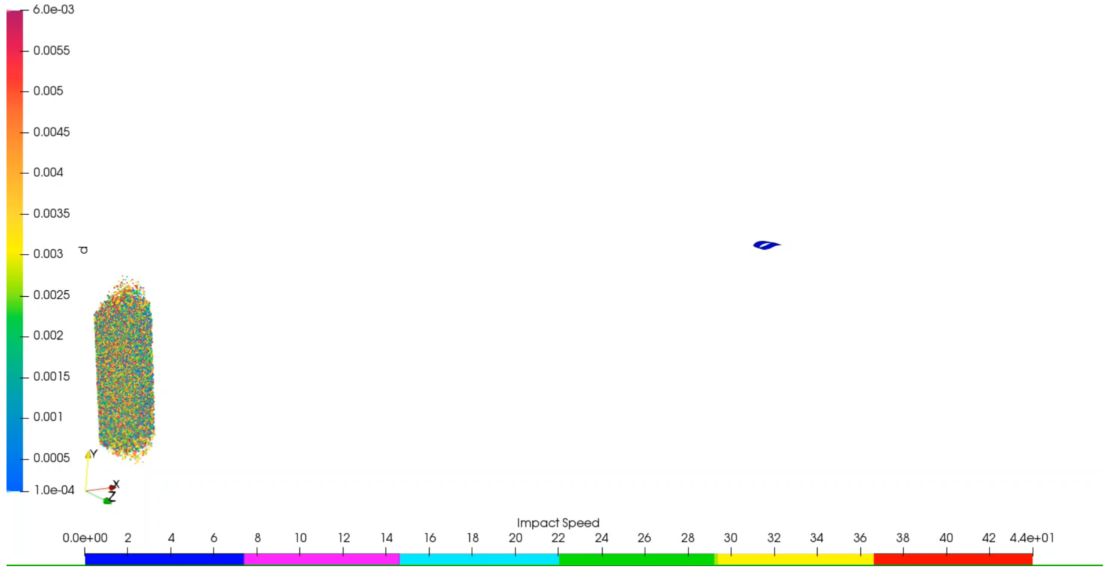

Fig. 2: Example of a LPT simulation for flow over a middle section airfoil of IEA15MW turbine (AoA=6.462°) [4]

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Method

- Rain Model:
  - Spherical Droplets
  - $R_h = 5\frac{mm}{h}$, $LWC = 0.0889{R_h}^{0.84} = 0.344\frac{g}{m^3}$ (Marshall & Palmer Rain Model [2])
  - $LWC = \frac{KQ}{U_\infty A}$ ➔ Particle Injection Rate
  - Injection parallel to flow (gravity neglected)

- Erosion Model:
  - $F_{impact} = \frac{m_p \cdot U^2_{impact,norm} \cdot n_p}{d_p}\ [kN]$ with p: particle

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LPT Simulation Results

Droplet size distribution

$$N(d_p) = N_0 e^{-Id_p}$$

Marshall & Palmer: $N_0 = 8000 \frac{m^{-3}}{mm^{-1}}$, $I = 4.1R^{-0.21} mm^{-1}$

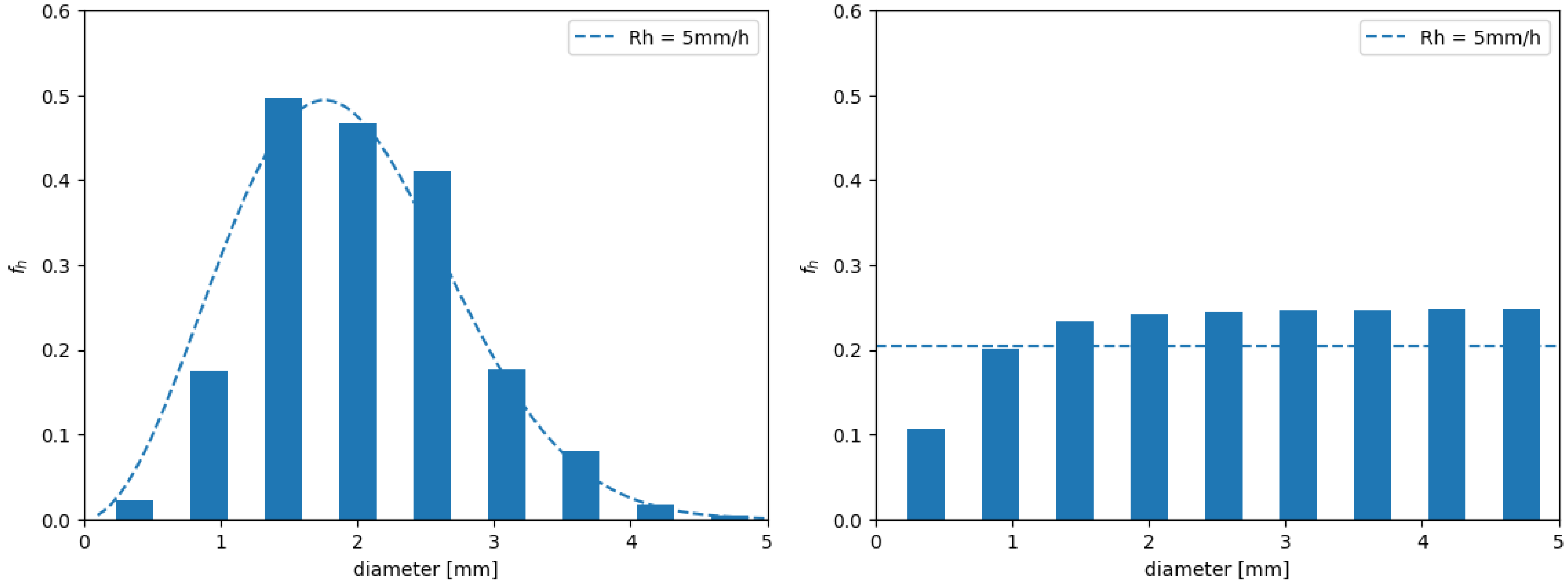

Fig. 3: Size distributions for impacted droplets for non-uniform (left) and uniform (right) input distribution (AoA=8°, here: std. Airfoil; dashed lines = input distributions)

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LPT Simulation Results

Normalized impact force rate over chord distance from stagnation point

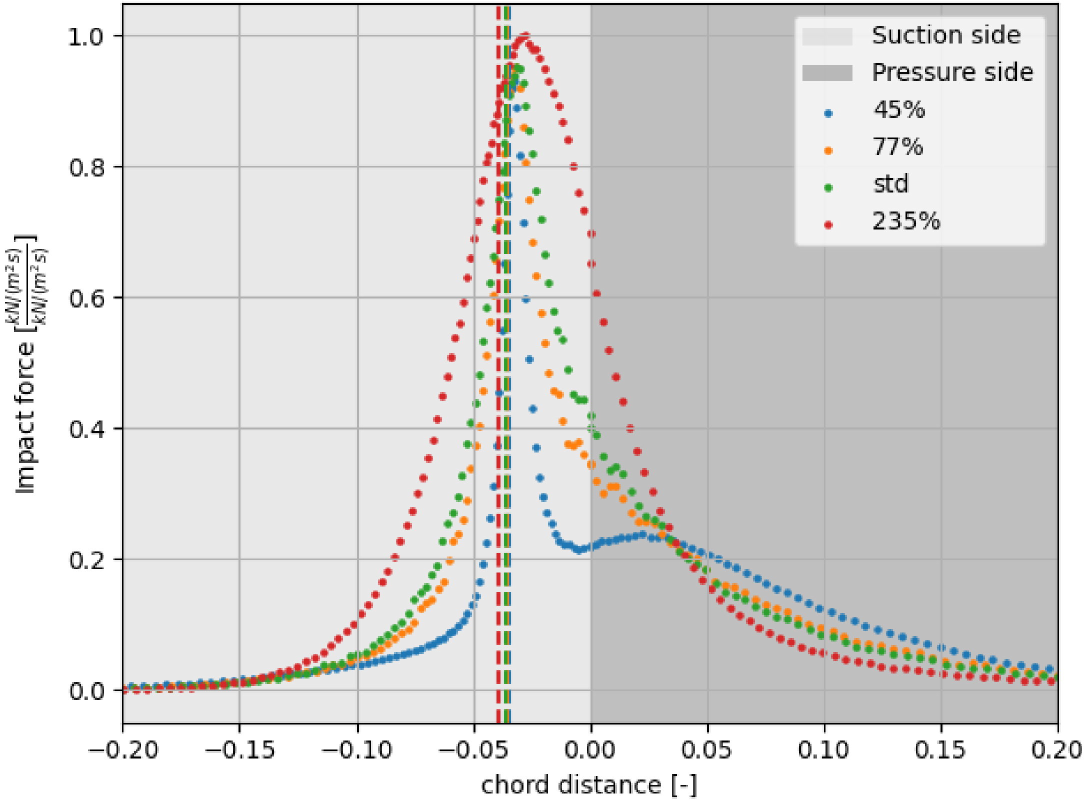

Fig. 4: Distributions of normalized impact force rates over chord distance from the stagnation point for the 3 LE radius modifications (dashed line = LE) (AoA=8°)

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LPT Simulation Results

Normalized impact force rate distribution around LE

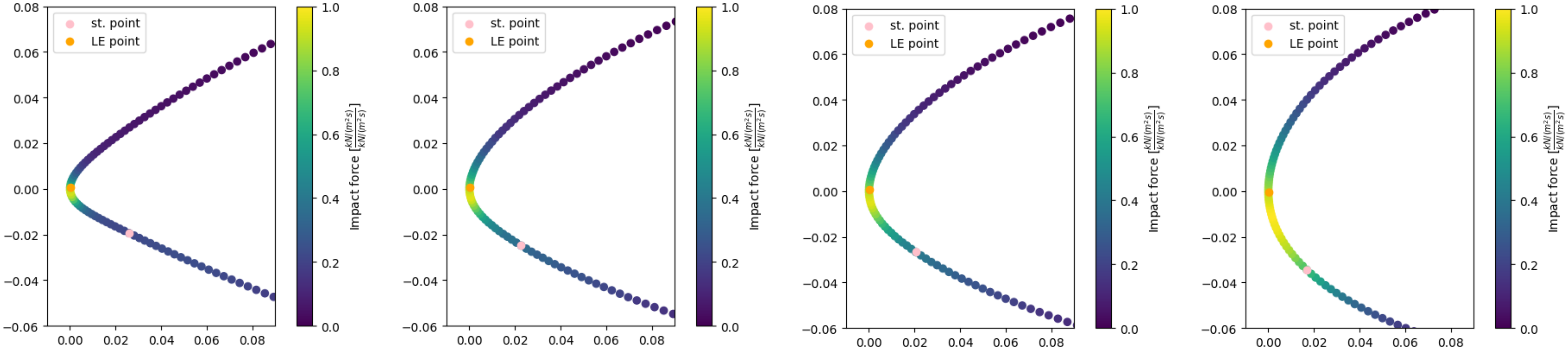

Fig. 5: Distributions of normalized impact force rates around airfoil front for the four LE radius modifications (AoA=8°)

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LPT Simulation Results

Normalized comparison of integral impact force rates

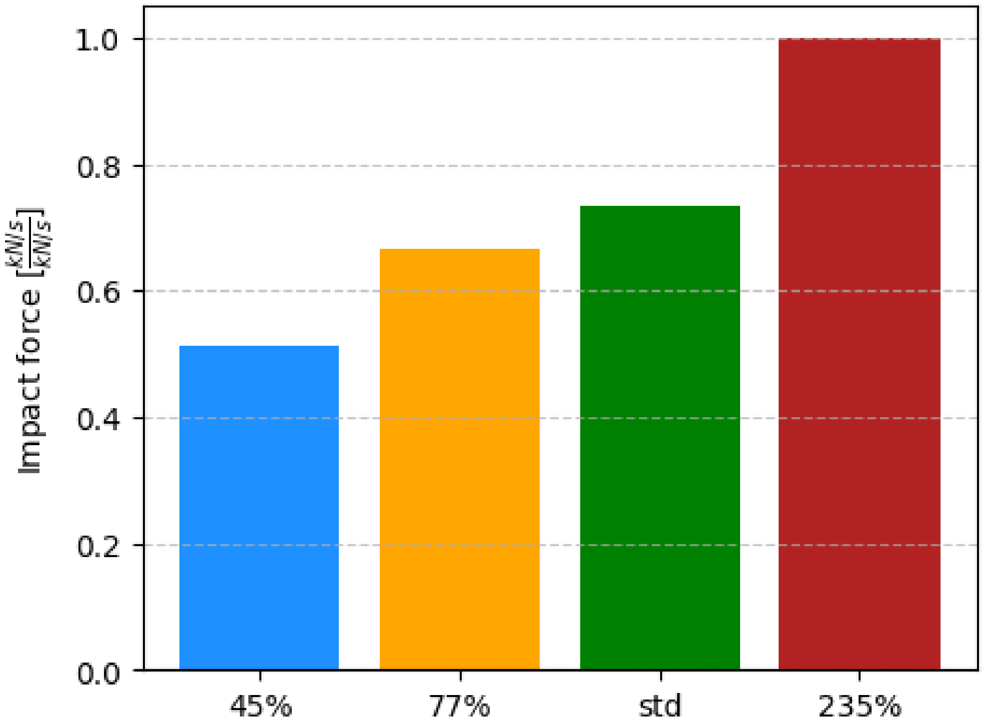

Fig. 6: Comparison of normalized integral impact forces per second on each airfoil surface (AoA=8°)

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Conclusions

- Method confirms observation of max. impact around the LE
- LE radius has no significant effect on diameter distribution, but influences impact force
- Regarding the impact force rate, airfoils with a larger LE radius experience:
  - Higher and wider peaks
  - More symmetrical distributions around the peak
  - Higher integral forces per unit time

➡ Confirms potential of airfoil design approach for reducing erosion

➡ First step in parameter space exploration for airfoil optimization

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Thank you for your attention!

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References

[1] The OpenFOAM Foundation. OpenFOAM: The Open Source CFD Toolbox, Version 2306. The OpenFOAM Foundation, 2023. https://www.openfoam.com

[2] J. S. Marshall and **W. Mc K. Palmer**. The distribution of raindrops with size. Journal of the Atmospheric Sciences, 5(4):165–166, 1948.

[3] N. Barfknecht and **D. von Terzi**. Aerodynamic interaction of rain and wind turbine blades: the significance of droplet slowdown and deformation for leading-edge erosion. Wind Energy Science, 9(12):2333–2357, 2024**[2]** [AIRE Project - Enhancing Wind Power Production]

[4] AIRE 3rd GA WP3

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Comparison: Gliding angle vs. AoA

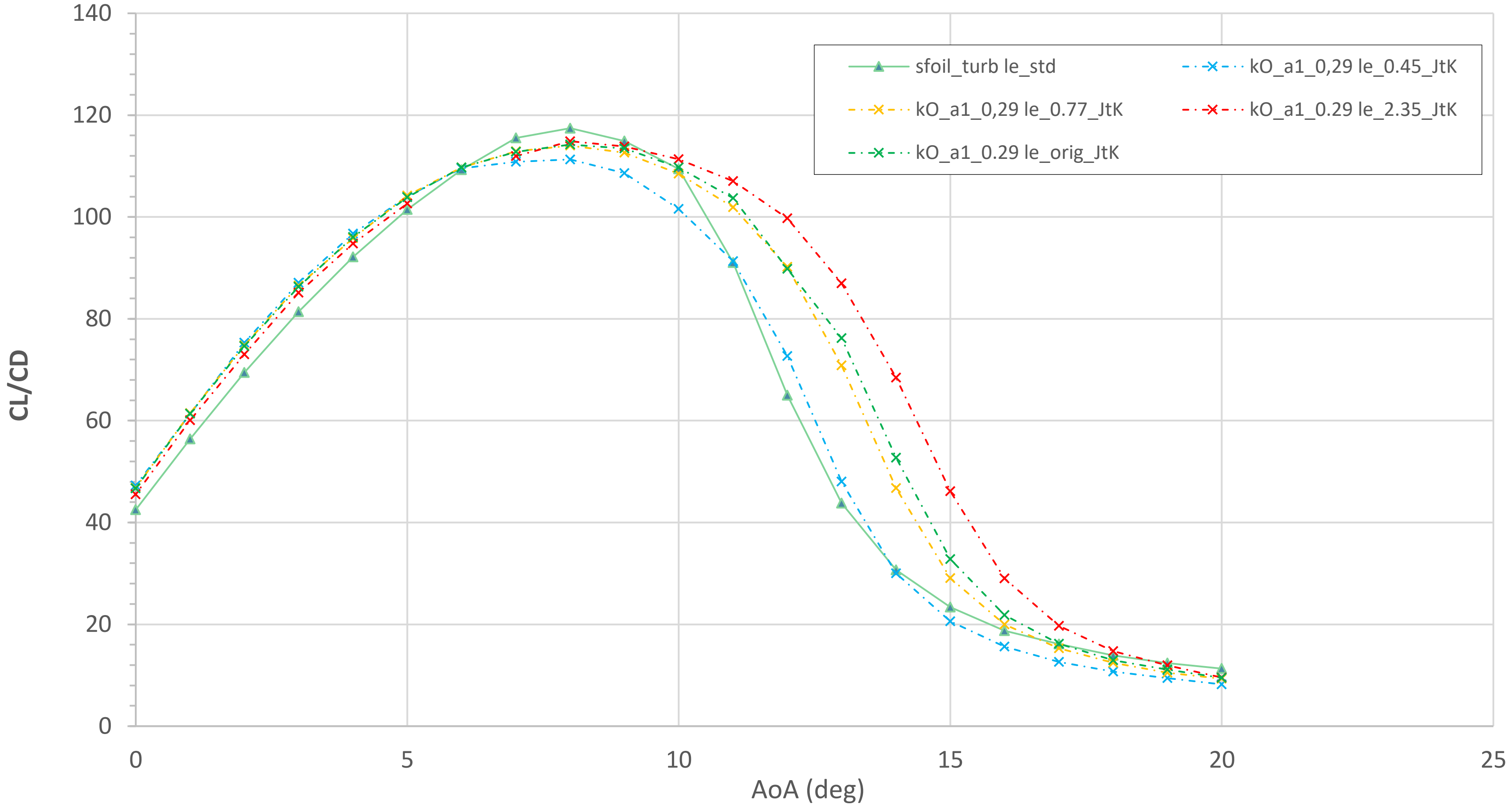

Fig. 7: Polars (CL/CD vs. AoA) of diff. LE-radii-airfoils, for OF k-ω SST simulations

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Rain Modeling

- $LWC = \frac{KQ}{U_\infty A}$
- Droplet Size Distribution: $N\left(d_p\right) = N_0 e^{-Id_p}$
- Marshall & Palmer Rain Model :
  - $LWC = 0.0889{R_h}^{0.84}$
  - $N_0 = 8000\frac{m^{-3}}{mm^{-1}}$, $I = 4.1R^{-0.21}mm^{-1}$

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CFD Simulations

- **Solver**
- *simpleFoam*, *icoUncoupledKinematicParcelFoam* [1]
- **Mesh**:
- Total no. of cells: 130560
- $y^+ = 0.75$
- Domain Size: > 30 chord lengths up- & downstream
- **Computational Expense:**
- Base Polar Runs: Clock Time ~ 30 mins over one 8-core-node
- LPT Simulations: of same order (600s simulated time for steady particle field)
- Post-Processing: Clock Time ~ 1 min over one 8-core-node, max. memory usage 4410.79 MB

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