WIND TURBINE AERODYNAMIC STUDY WITH OPENFOAM

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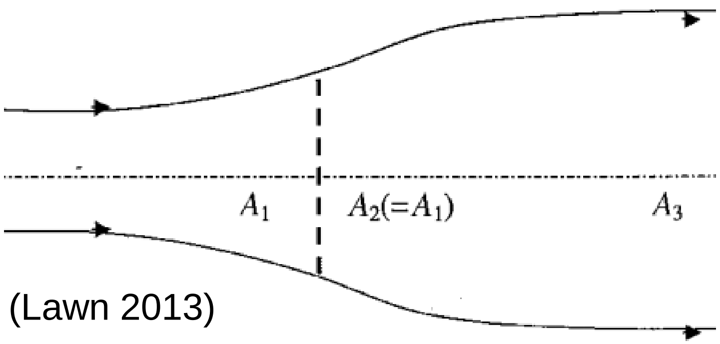
Contents

1. Introduction

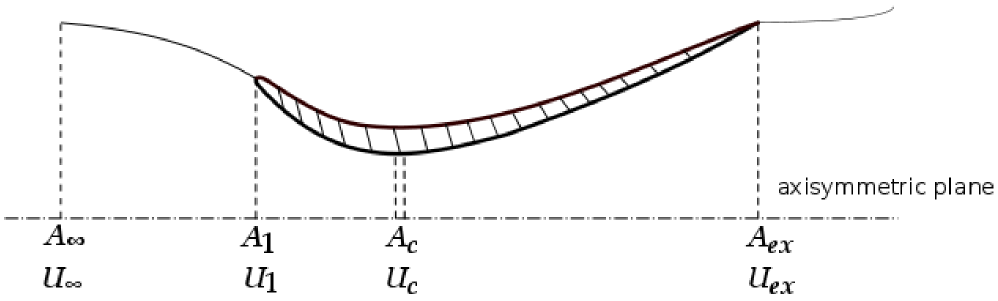
- The extractable energy of a horizontal-axis turbine rotor of fixed size can be increased by installing it at the entrance of a diffuser.
- The aim of this work is to analyze the influence of the pressure losses of a diffuser augmented wind turbine (DAWT) in the extractable power.

- The diffuser produces a greatly reduced pressure behind the turbine compared to the one behind a bare turbine.



(Lawn 2013)

Bare turbine

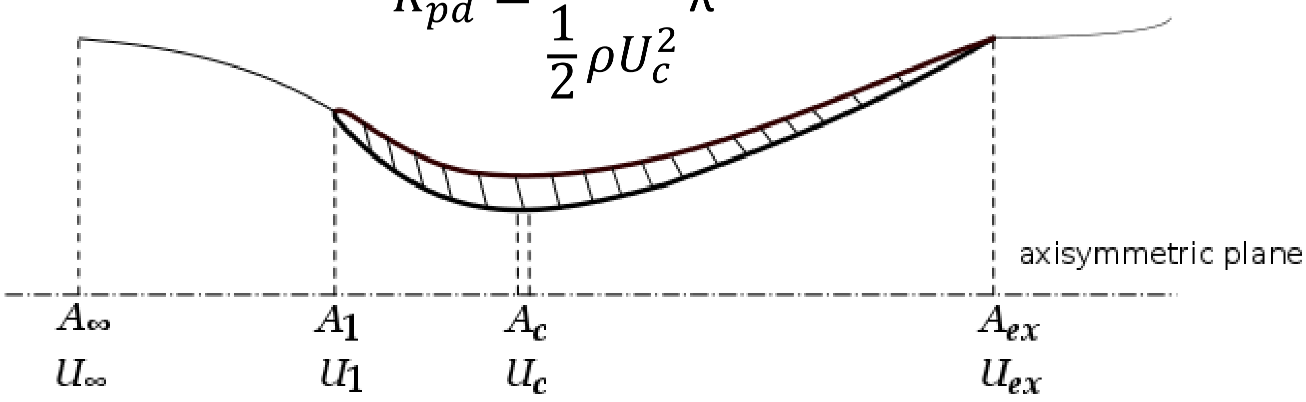


Ducted Turbine

- This effect increases the mass flow-rate through the DAWT duct, with at least as much pressure change as across a conventional turbine.

- The increase of mass flow-rate in the diffuser is influenced by four main factors:
    - The diffuser area ratio. $\lambda = \frac{U_c}{U_{ex}} = \frac{A_{ex}}{A_c}$
    - The base pressure reduction at the diffuser exit caused by the obstruction flow.
    - The flow separation downstream in the diffuser. $c_{pex} = \frac{p_{ex} - p_\infty}{\frac{1}{2}\rho U_\infty^2}$
    - Viscous losses.

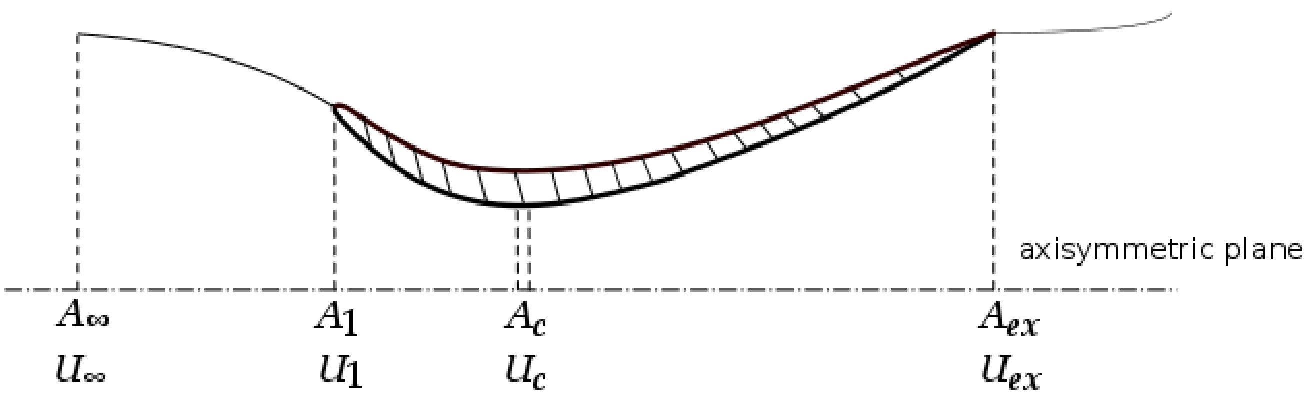
$$K_{pd} = \frac{\Delta p_d}{\frac{1}{2}\rho U_c^2}\lambda^2$$



2. Analytical Framework

$$p_\infty + \frac{1}{2}\rho U_\infty^2 = p_{ex} + \frac{1}{2}\rho U_{ex}^2 + \Delta p_c + \Delta p_d,$$

$$K_{pc} = \frac{\Delta p_c}{\frac{1}{2}\rho U_c^2}\lambda^2, \qquad c_{Wc} = \frac{\Delta p_c U_c A_c}{\frac{1}{2}\rho A_c U_\infty^3} = K_{pc}\lambda\left(\frac{U_{ex}}{U_\infty}\right)^2.$$



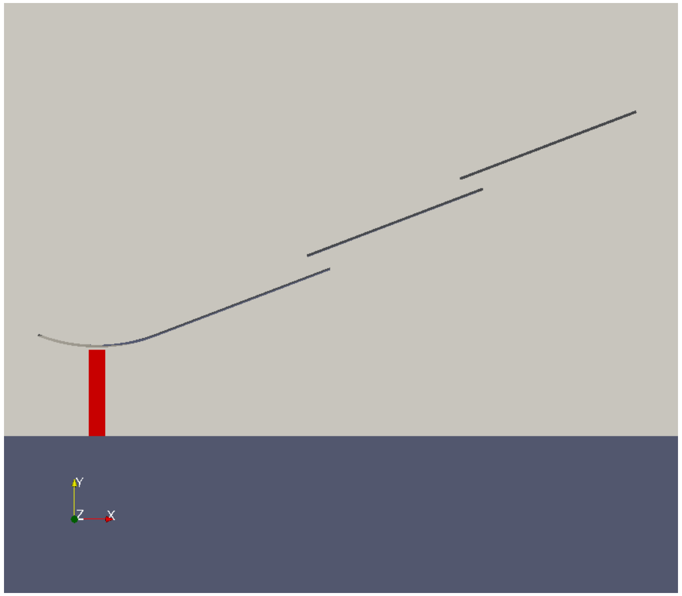
- Parameter to compare different DAWT duct configurations

$$c_{Wc} = \frac{\Delta p_c U_c A_c}{\frac{1}{2}\rho A_c U_\infty^3} = K_{pc}\lambda\left(\frac{U_{ex}}{U_\infty}\right)^2 .$$

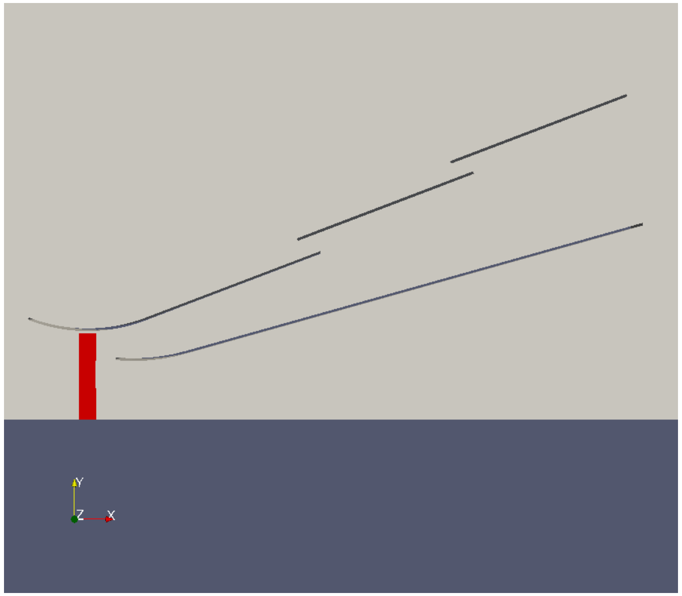
- Betz's Limit: $c_{Wc} = 0.593$, $K_{pc} = 2$
- Objective → Maximize c_{Wc}

Analyzed Configurations

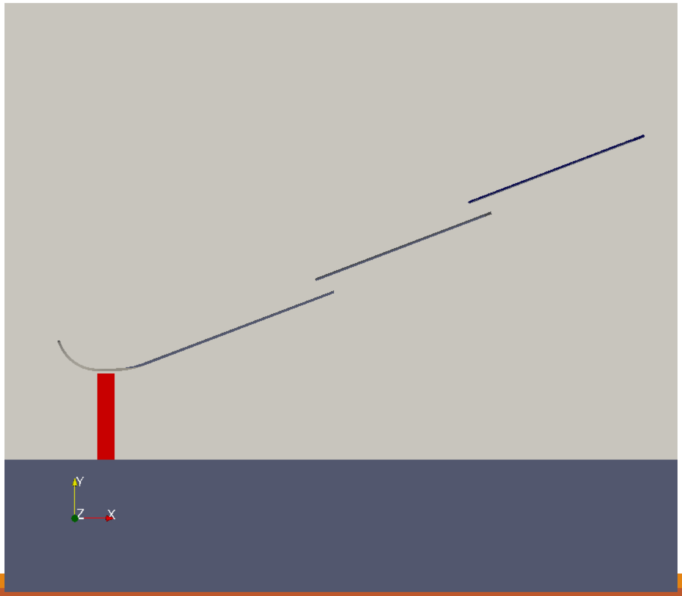
1a



1b



2a



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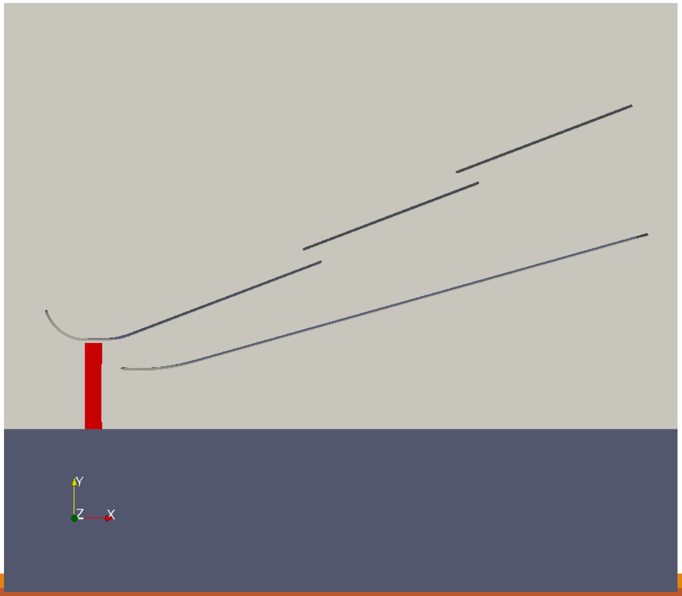
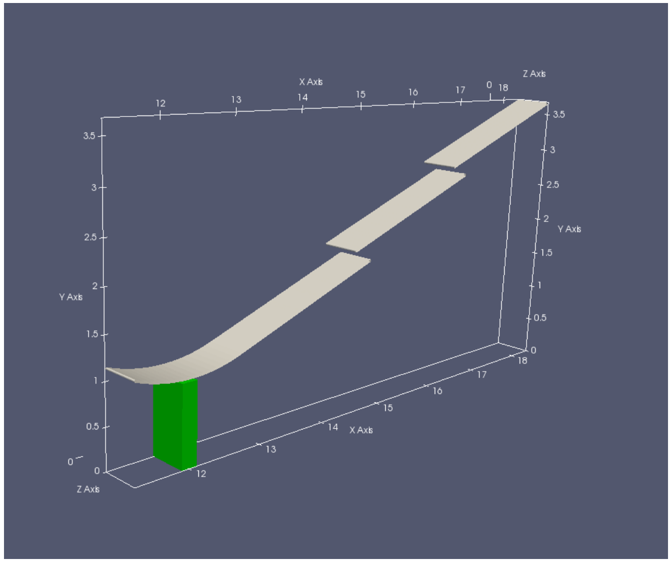


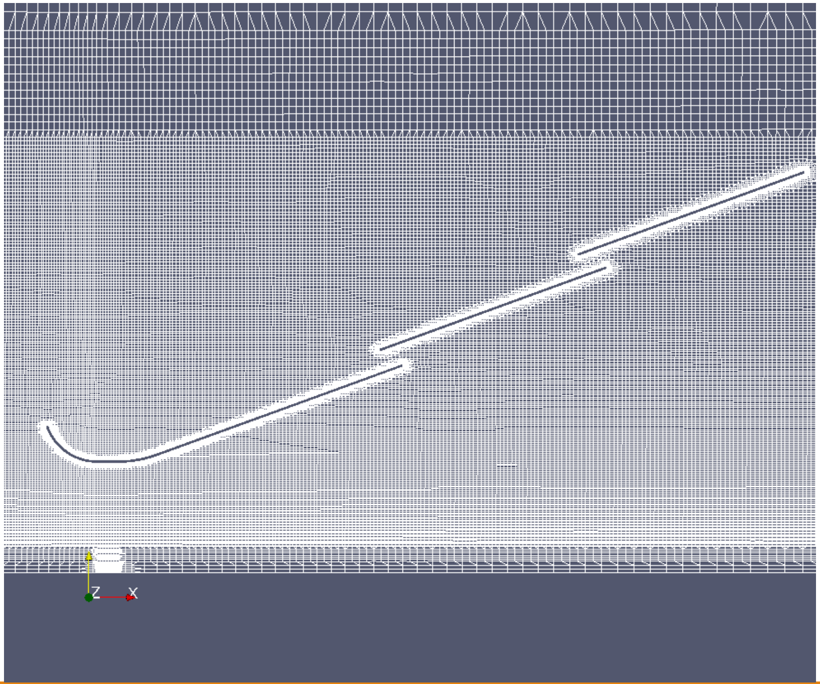
3. Numerical Setup

- Steady RANS equations
- Solver: porousSimpleFoam
- Scheme: 1^{st}
- Turbulence Model: $k-\varepsilon$
- Reynolds number: $Re \approx 550\,000$ on the turbine section
- Freestream velocity: $U = 4$ m/s

Computational Domain

- 60x24x0.5 m
- Geometry generation with Salome and python
- Mesh generation with snappyHexMesh
- Nº cells ≈ 130 000
- Duct length 17 m
- $\lambda = \frac{U_c}{U_{ex}} = \frac{A_{ex}}{A_c} = 3.7$



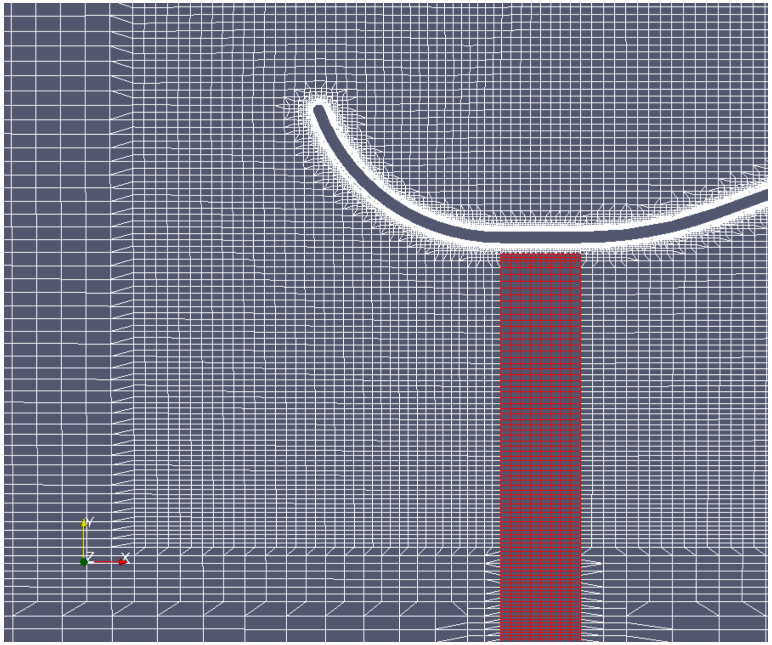


Porous Region

- 2D model, using a porous region as an actuator disk
- Darcy-Forchheimer formulation
- Just inertial terms (*F*) were considered
- Momentum equation in this region:

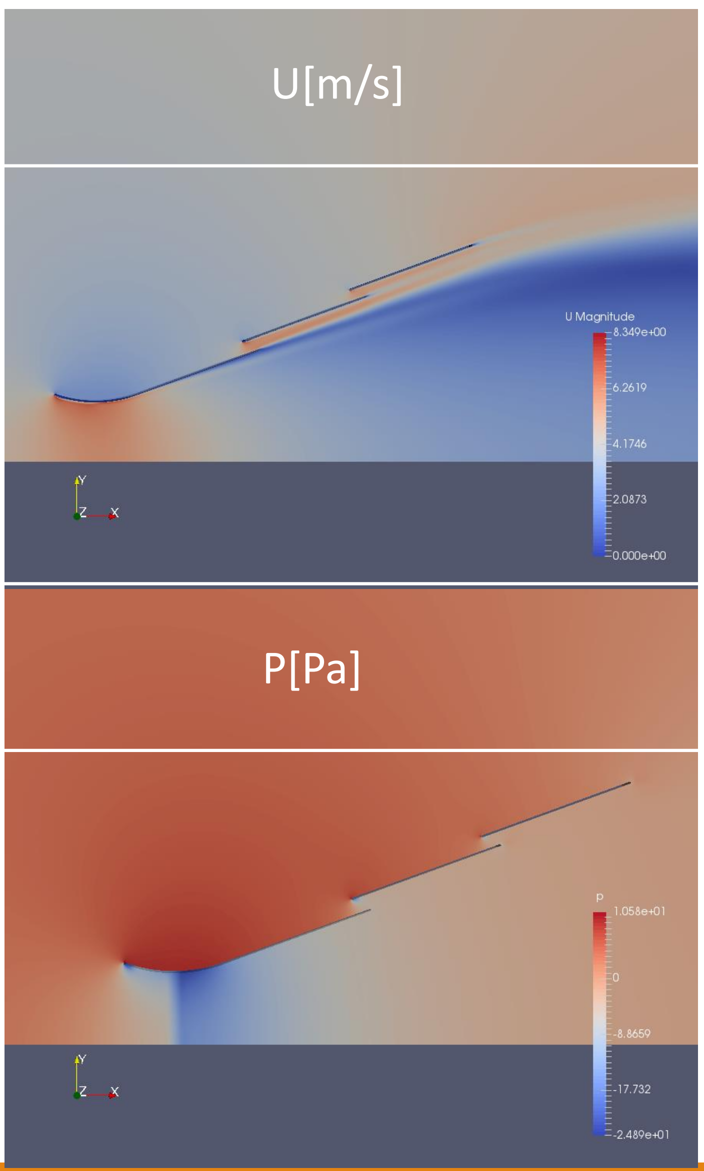
$$u_j \frac{\partial}{\partial x_j}(\rho u_i) = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial \tau_{ij}}{\partial x_j} + S_i$$

$$S_i = -\left(\mu D + \frac{1}{2}\rho |u_{jj}| F\right) u_i$$

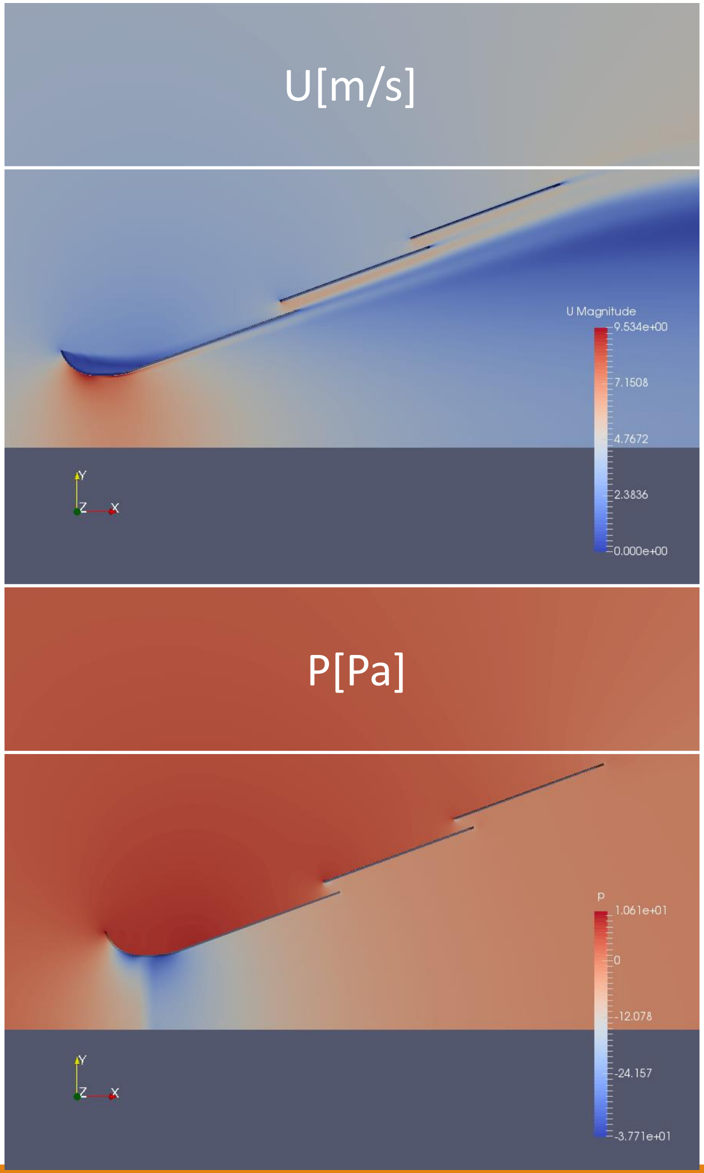


4. Results

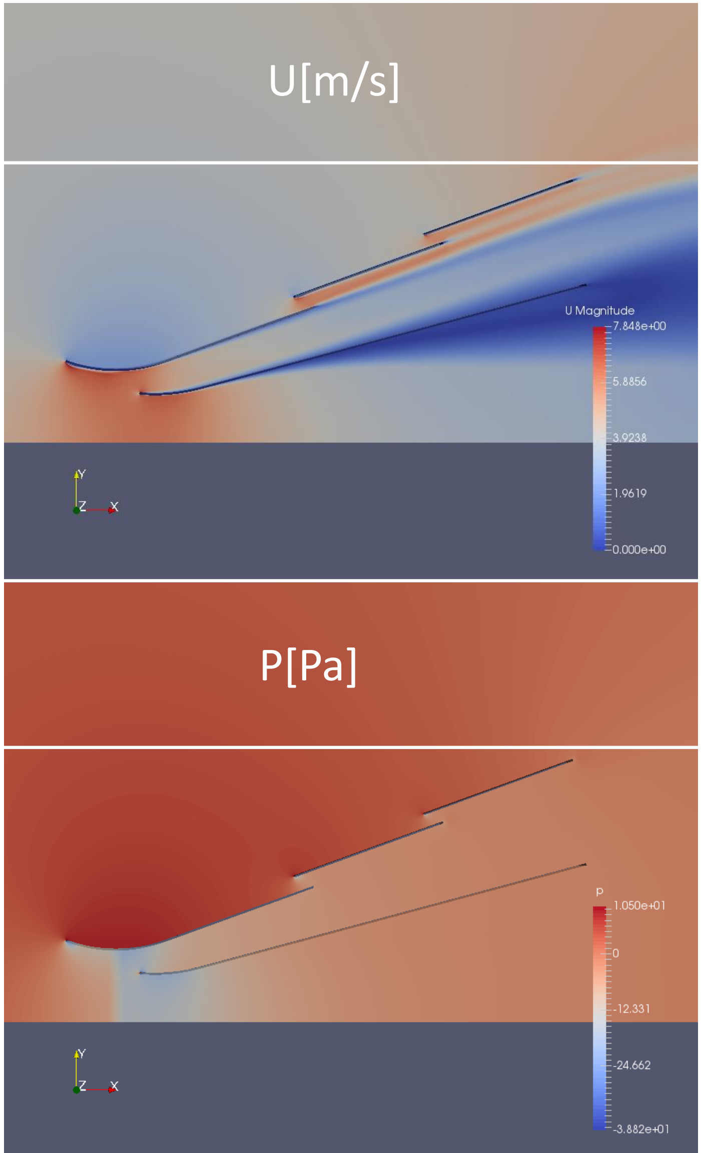
1a



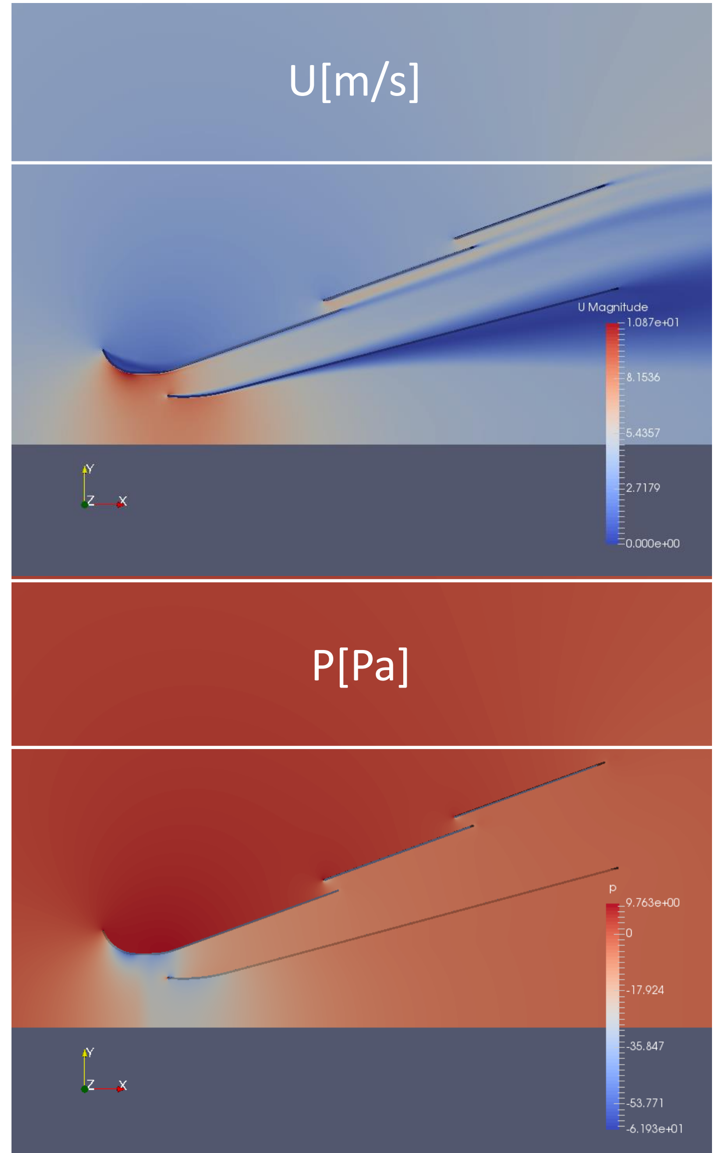
2a



1b


U[m/s]
U Magnitude
7.848e+00
5.8856
3.9238
1.9619
0.000e+00
P[Pa]
p
1.050e+01
0
-12.331
-24.662
-3.882e+01

2b


U[m/s]
U Magnitude
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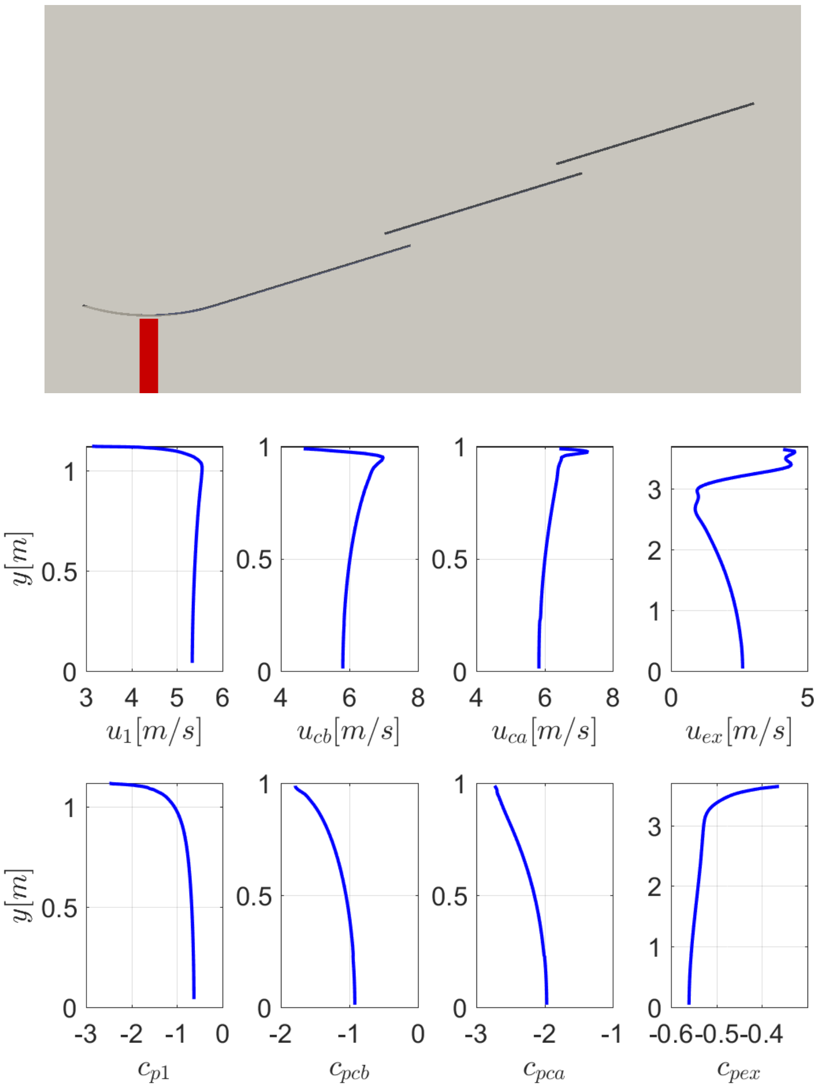
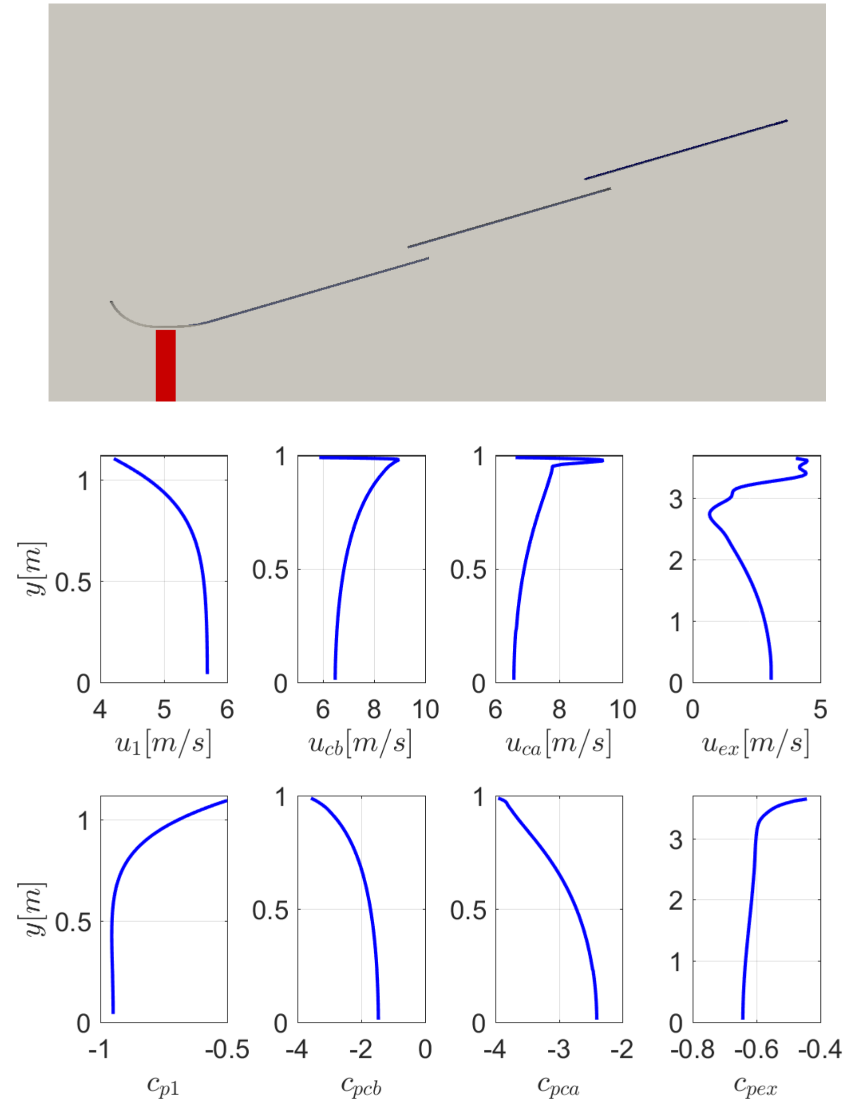
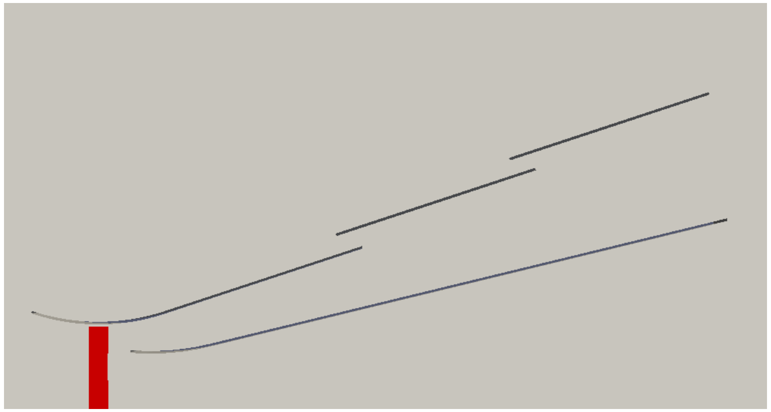
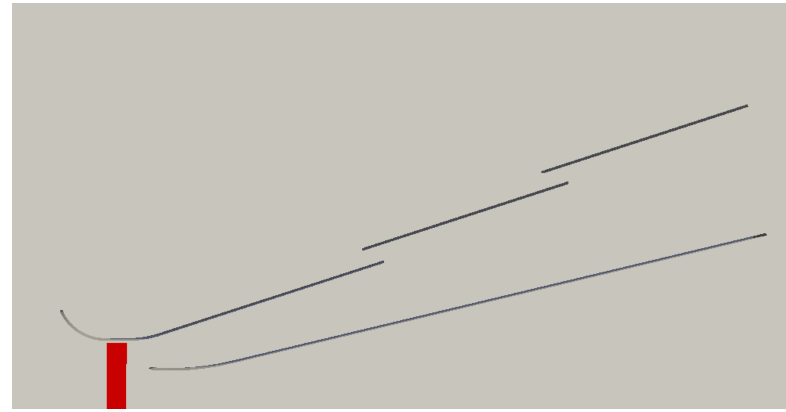
5.4357
2.7179
0.000e+00
P[Pa]
p
9.763e+00
0
-17.924
-35.847
-53.771
-6.193e+01

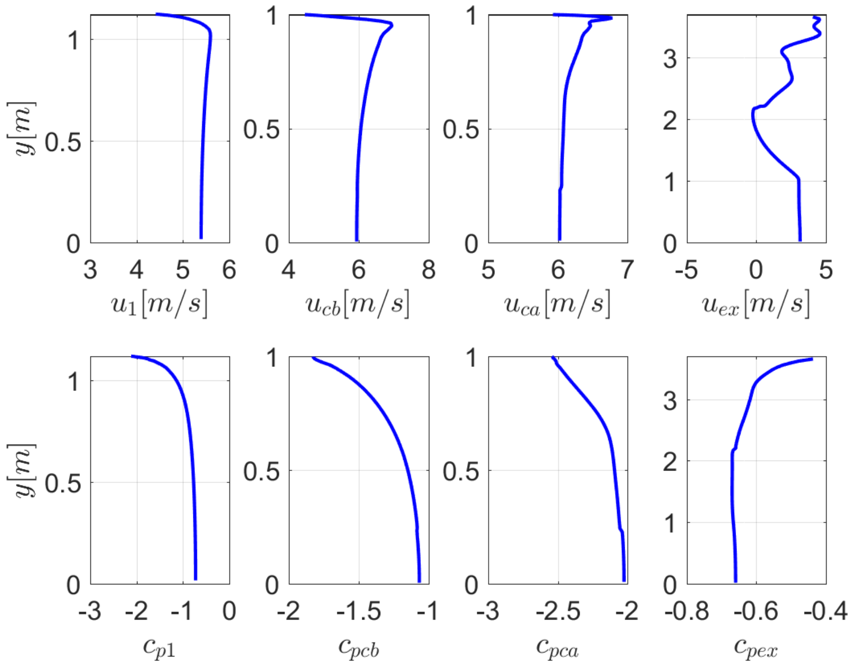
Velocity and pressure coefficient profiles

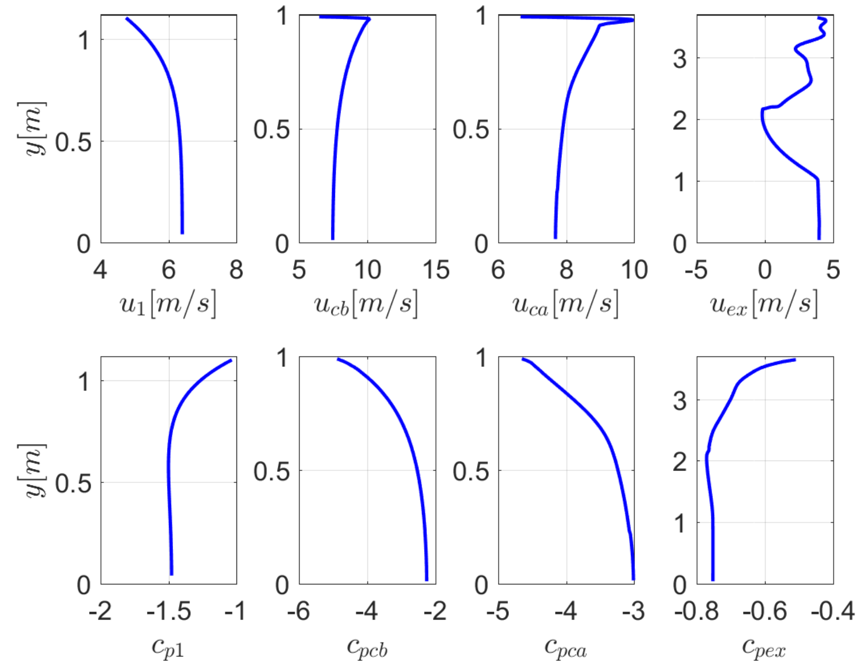




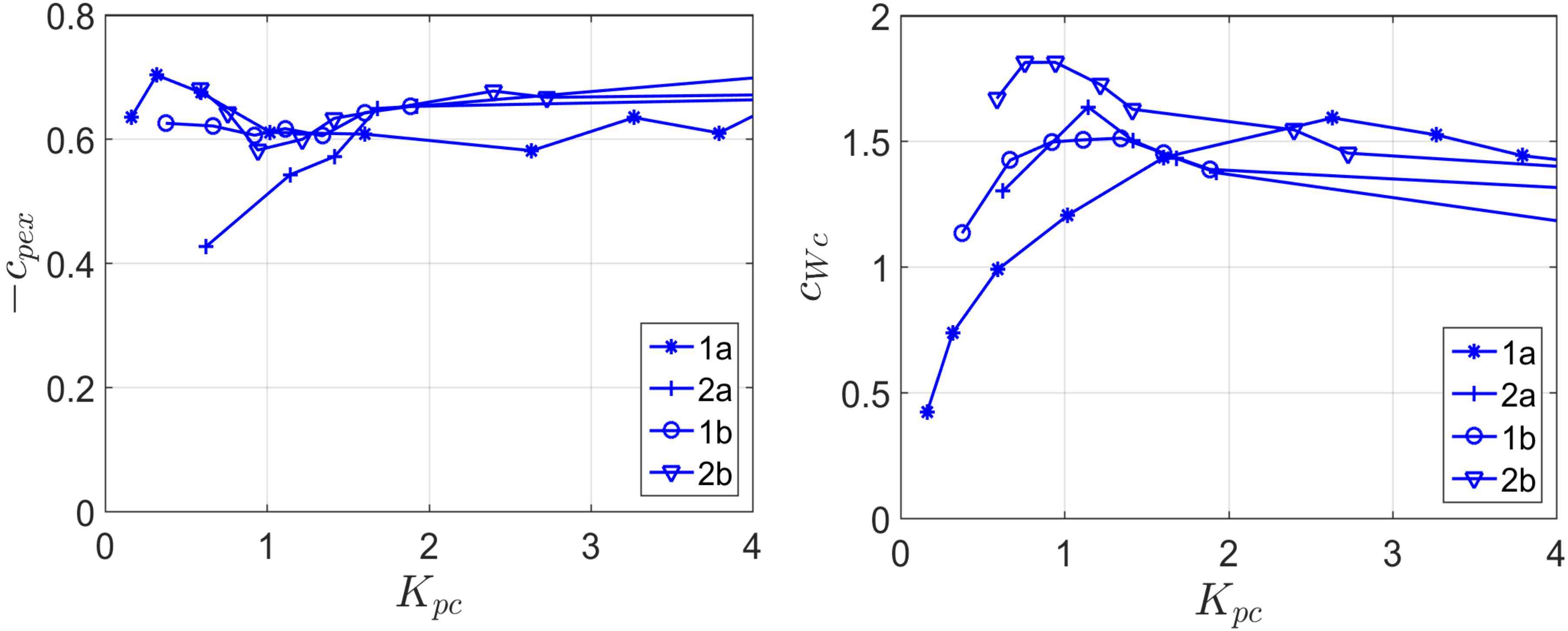


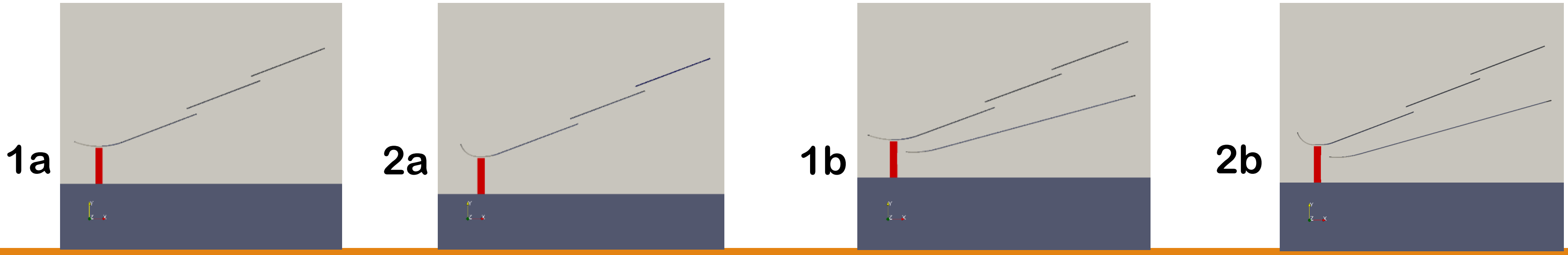



y[m]
u1[m/s]
ucb[m/s]
uca[m/s]
uex[m/s]
cp1
cpcb
cpca
cpex


y[m]
u1[m/s]
ucb[m/s]
uca[m/s]
uex[m/s]
cp1
cpcb
cpca
cpex

Pressure coefficient at the turbine exit and specific power extracted





5. Conclusions

- The simulations show the importance of a well design entrance to reduce pressure losses due to flow detachment.

- Comparing configurations 1a) and 1b), the effect of the vane is a reduction of the energy extracted. However, once the entrance was improved, the vane implies an increase of the energy extracted.

- The obtained values of c_{Wc} exceed the Betz limit for all configurations.

- When the efficiency of the entrance increase, the maximum of c_{Wc} occurs for smaller values of K_{pc}, which is in accordance to Lawn (2003).

Thank you for your attention