EG – D03: MSc Part 2 Dissertation

Dept. of Mechanical Engineering

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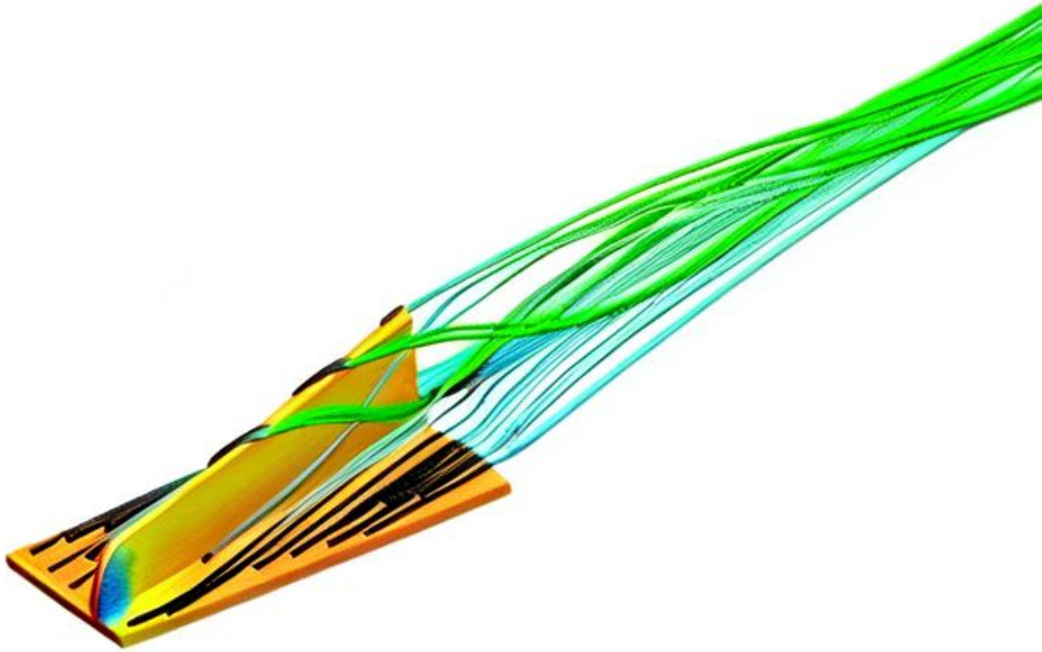
Swansea University
Prifysgol Abertawe

CFD Investigation into the Effect of Flow Control Mechanisms on Tidal Turbine Performance



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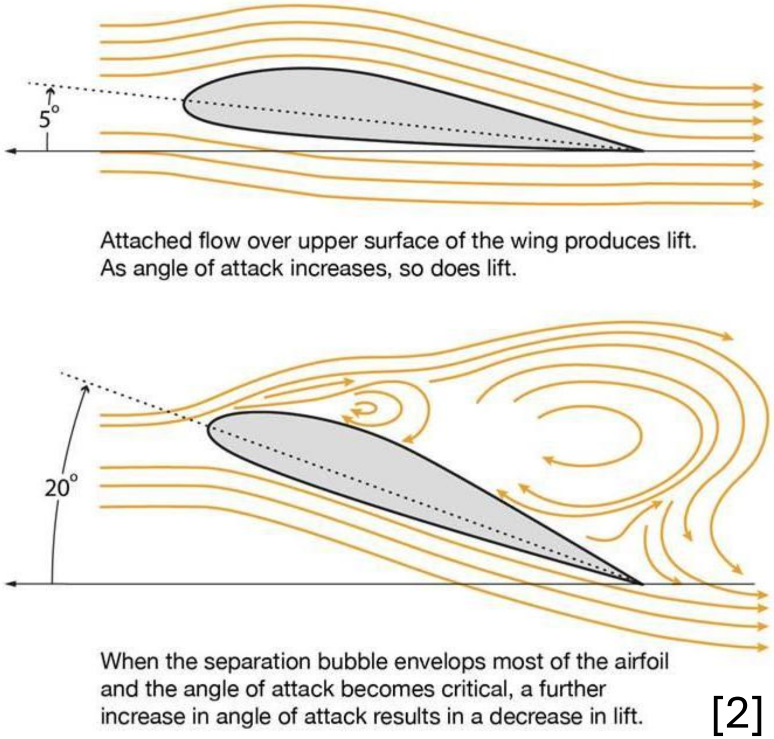
Flow separation

Flow separation occurs when the boundary layer fails to maintain attached flow at higher angle of attacks of airfoil, leading to reversed flow resulting in reduced blade efficiency and higher fatigue loads.

- Separation also causes stall, where the blade can no longer generate useful lift.
- These effects reduce the power output, increase structural loading, and can lead to performance instability.
- Flow control mechanisms are necessary to help counter these problems by keeping the flow attached for longer.



Attached flow over upper surface of the wing produces lift. As angle of attack increases, so does lift.

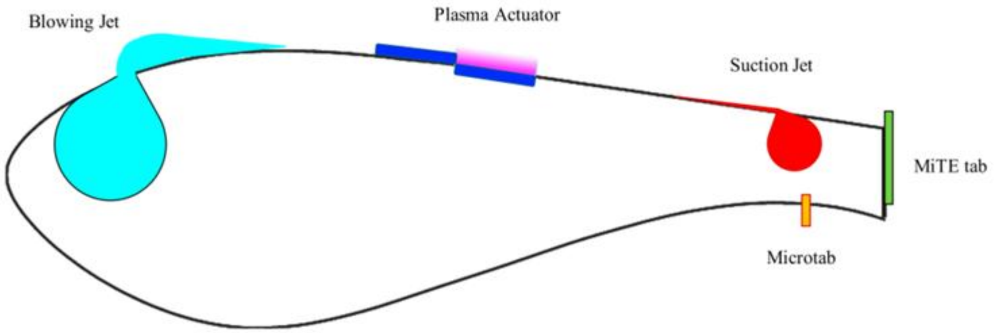
When the separation bubble envelops most of the airfoil and the angle of attack becomes critical, a further increase in angle of attack results in a decrease in lift.

[2]

Flow control mechanisms

Flow control mechanisms change the flow characteristics of the medium by controlling the movement of the fluid to achieve the effect of aerodynamic performance enhancements [10.54254/2753-8818/26/20241094].

- Types
  - Active
    - Suction
    - Blowing
    - Plasma actuators
  - Passive
    - Vortex Generators
    - Flaps
    - Microtab



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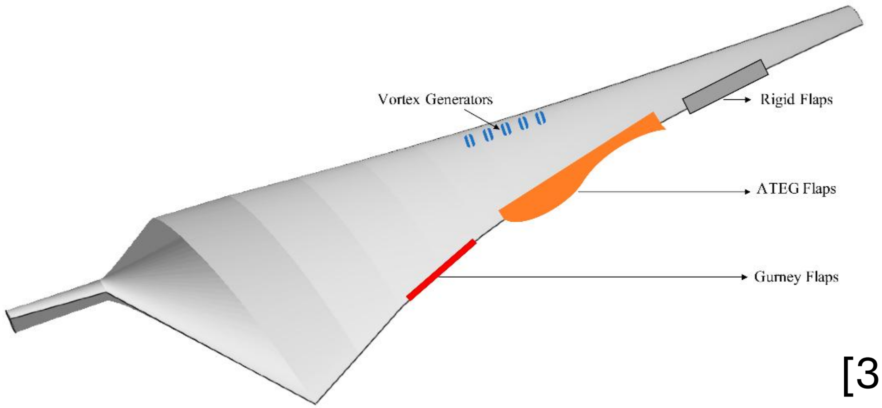

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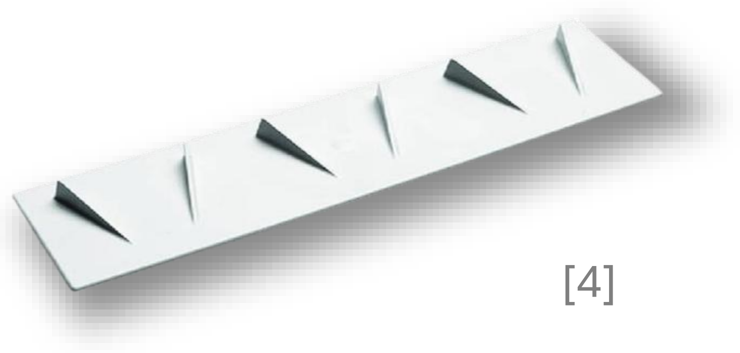
Vortex Generators

Vortex Generators (VGs) are small vanes or fins mounted on the blade that forms a streamwise vortex, carrying high-momentum fluid from outside the boundary layer closer to the surface.



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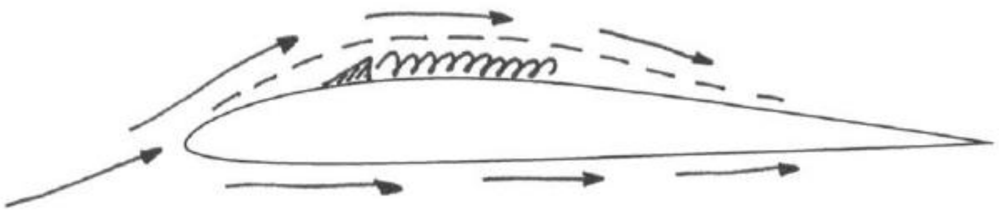
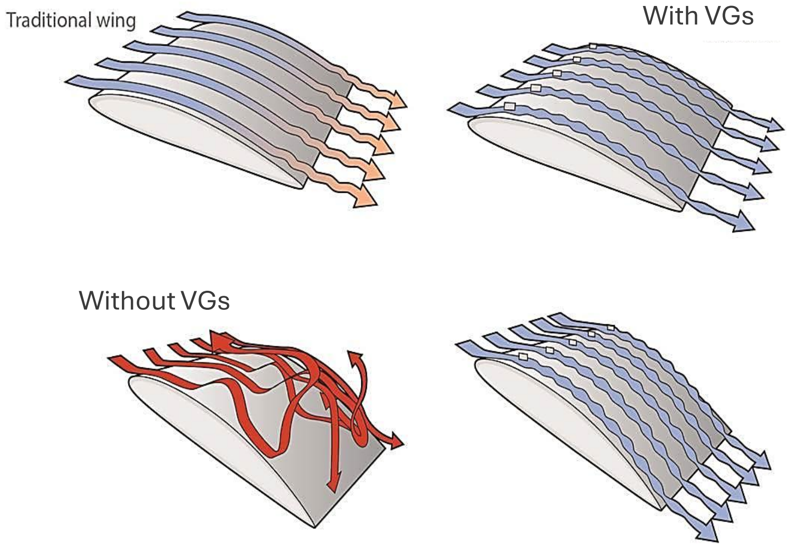


[5]

- VGs help in delaying flow separation, which occurs when the smooth airflow breaks away from the surface at higher angle of attacks, causing a loss of lift and huge increase in drag.
- They work by creating tiny swirling motions of fluid (vortices) that mix the faster particles from outside the boundary layer with the slower particles near the surface.
- This keeps the flow attached to the surface for longer, helping the blade produce more lift and delay stall.



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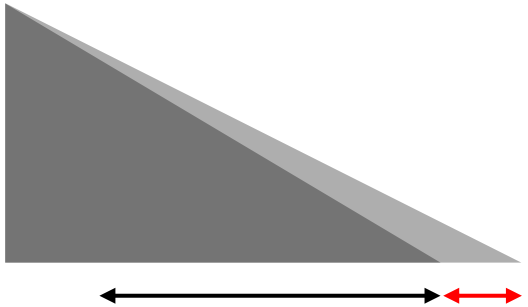
VG parametric study

Rectangular vane series: **R1 – R3**
Triangular vane series: **T1 – T3**

- The performance of vortex generators (VGs) depends strongly on their geometric configuration and placement.
- Vane-type VGs were parametrically varied in terms of:

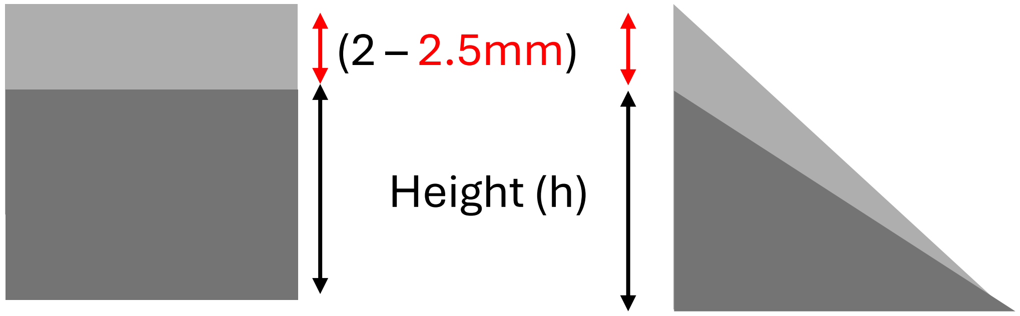
Length (L) (8 - 10mm)

R1 – R3



Length (L) (8 - 10mm)

T1 – T3

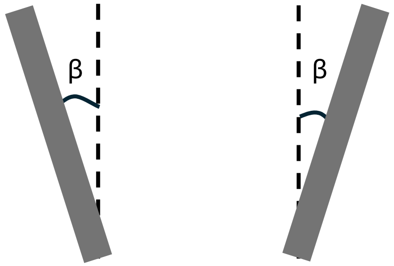


(2 – 2.5mm)

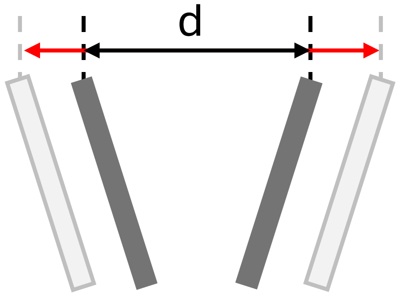
Height (h)

R1 – R3

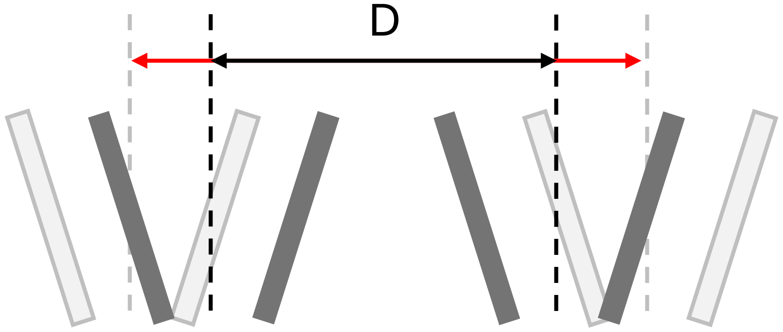
T1 – T3



Angle of Incidence (β)
T1 – T3: 10° to 15°
R1 – R3: 10° to 20°



Inter pair distance(d)
(8.75 – 10 mm)



Intra pair distance(D)
(8 – 10 mm)

Scope of present study

Hydrofoil shape selection

- Reviewed different hydrofoil profiles suitable for tidal turbine applications
- NACA 63-618 was selected for its favourable lift-to-drag ratio and sensitivity to flow separation in tidal applications.

Baseline hydrofoil CAD

- Baseline hydrofoil model with chord length of 250mm and span of 500 mm modelled using SolidWorks.
- A rectangular flow domain was built around the hydrofoil, extending sufficiently upstream and downstream.

Baseline Hydrofoil CFD

- Baseline Hydrofoil performance was assessed for tidal conditions at 1.5 m/s.
- Equivalent air speed was calculated and CFD simulations were performed for wind tunnel testing.

Hydrofoil with VG CAD

- Modelled hydrofoil with different configurations of VGs integrated.
- The domain was modelled around every hydrofoil.

Hydrofoil with VG CFD

- Tested different configurations of vane-type vortex generators (VGs) on NACA 63-618 hydrofoil performance.
- CFD simulations were performed for tidal case.

Airfoil with VG model

- The airfoil model was 3D printed, with a removable VG base to allow quick swapping of different configurations.
- Aluminium tape was applied at the front junction of the VG base to minimise flow distortions.

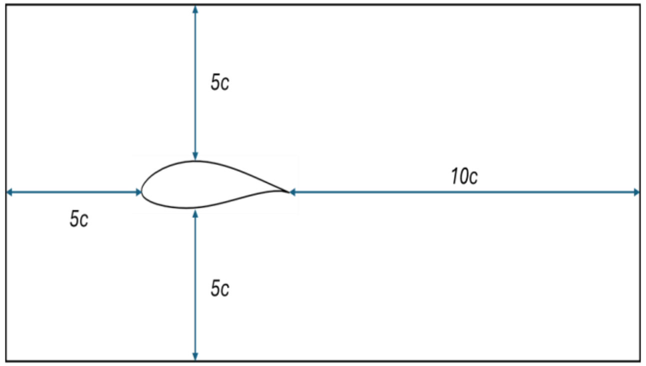
Wind tunnel testing

- Baseline airfoil followed by airfoil with VGs of different configurations were tested in the wind tunnel.
- Lift and drag coefficients were measured at 22 m/s wind speed to compare with CFD predictions across a range of angles of attack.

CFD set up

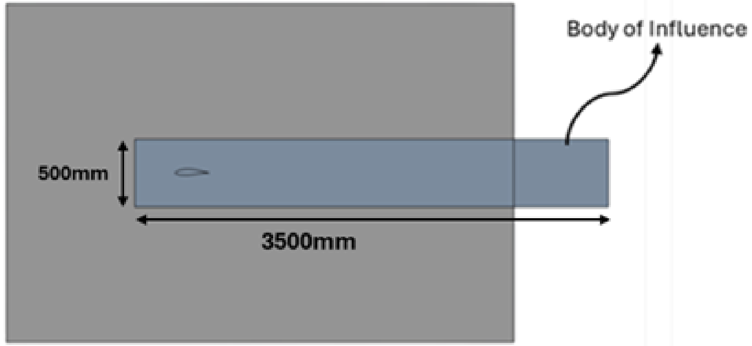
- ANSYS Fluent steady state RANS solver used.
- Pressure-based solver with the SST k-ω turbulence model.

Fluid Parameters	Water at 20 ˚C	Air
Density	1025 kg/m^3	1.225 kg/m^3
Dynamic Viscosity	1.003×10^{-3} Pa·s	1.789×10^{-5} Pa·s



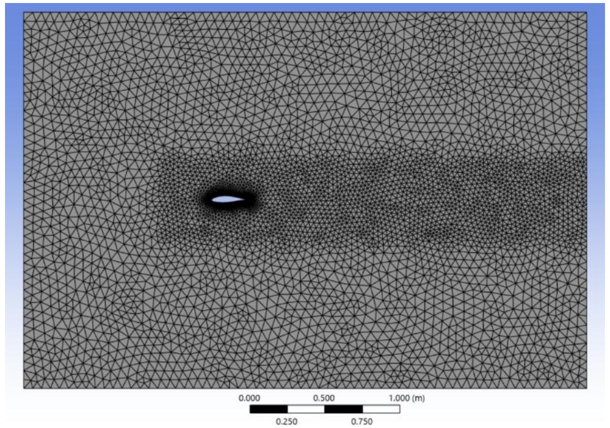
The domain modelled was :

- 5 chord lengths upstream.
- 10 chord lengths downstream.
- 5 chord lengths in the vertical directions above and below



Body of Influence (BoI) dimensions:

- Length: 3500mm
- Height: 500 mm
- Beginning 250 mm upstream of the hydrofoil’s leading edge.

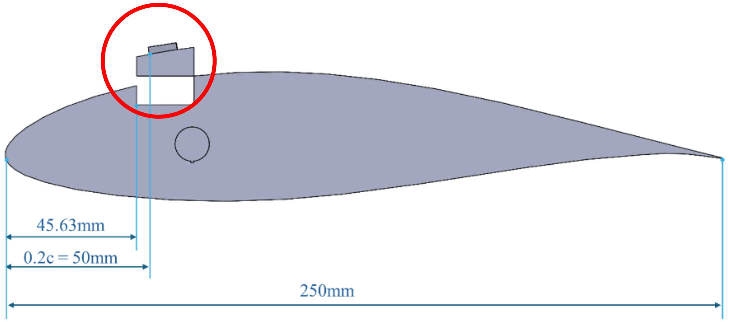


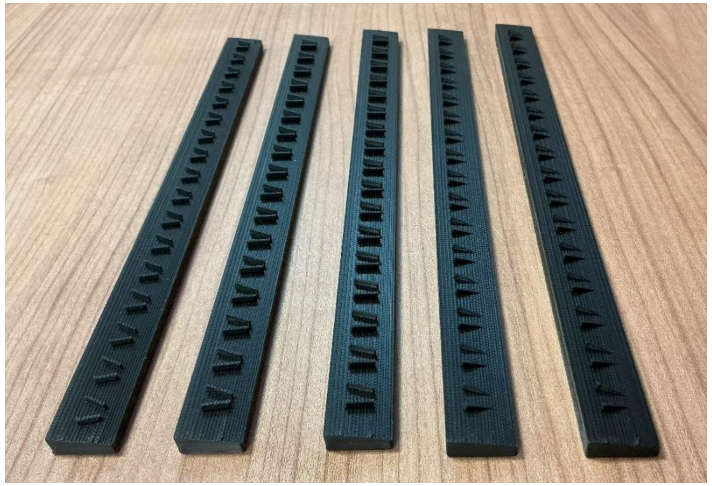
Mesh:

- Element size: 0.05m
- Inflation layers: 10
- BoI sizing: 0.045m

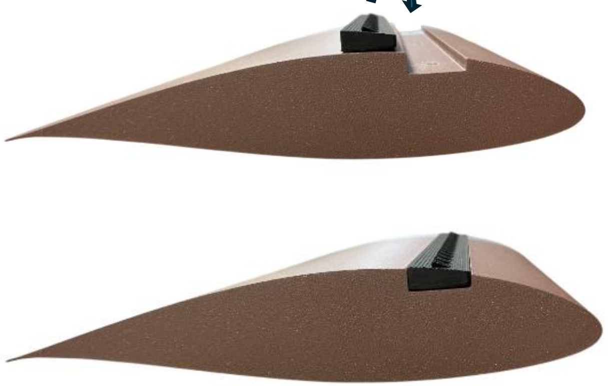
Wind Tunnel set up

- A section of the airfoil was cut-out, which served as a base for the vortex generators.
- The base sits at 0.2c distance from the leading edge
- VG bases could be removed and swapped between test cases easily, secured in position using magnets.
- Material used for printing: PLA




Vortex generator swappable bases


Magnets attached to slot and base


Mounting method

Wind Tunnel set up

- Model was tested in Swansea University's AF-100 subsonic wind tunnel by Techquipment$^{\text{TM}}$.
- Working section of 0.305m × 0.305m × 0.6m with a clear roof, sides and floor
- All relevant data, like the angle of attack, lift, drag, and wind tunnel speed, are captured using the Versatile Data Acquisition System (VDAS) software.
- The airfoil model was positioned in an inverted orientation, causing the lift force to act downwards, which aligns with the natural direction of gravity and simplifies the calibration of the force balance.

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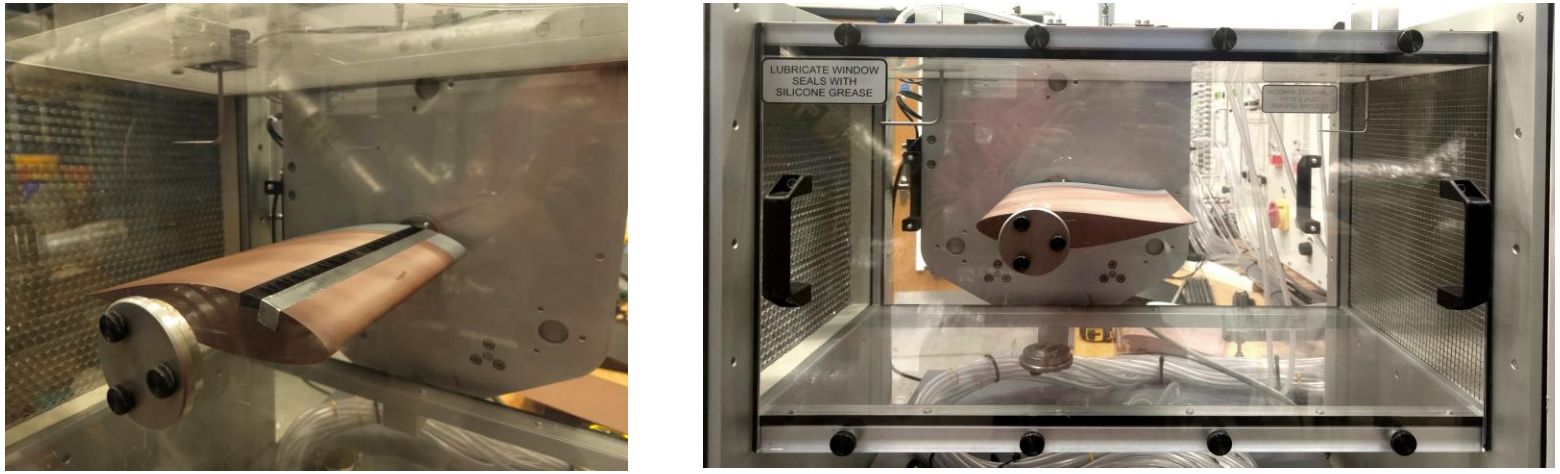
AF -100 Subsonic Wind Tunnel

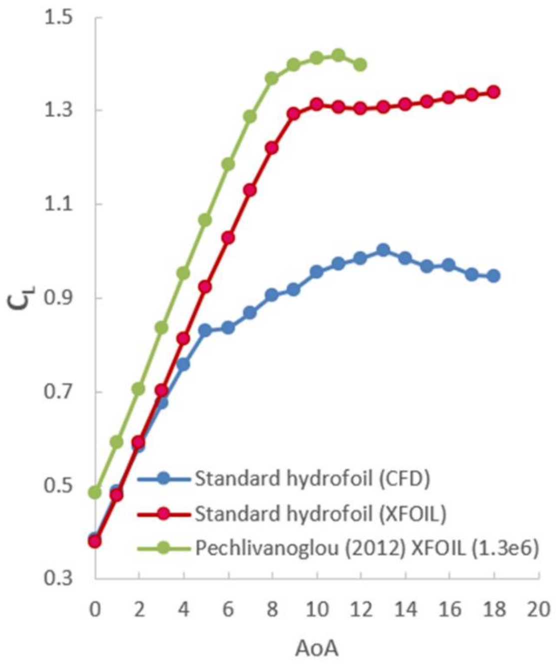
Tested at wind speed:

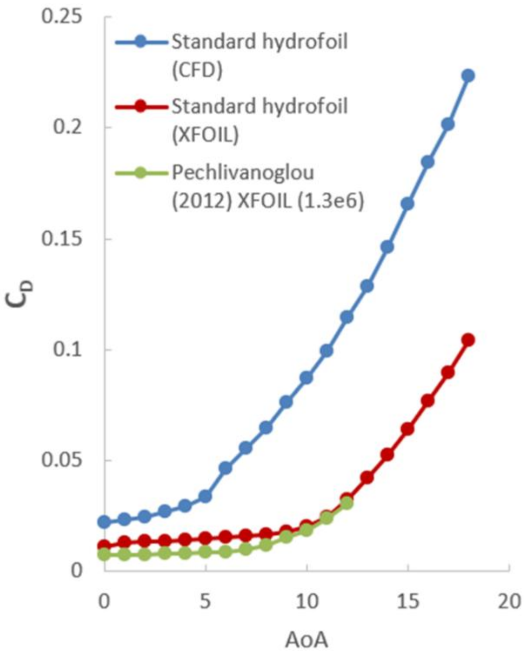
22m/s

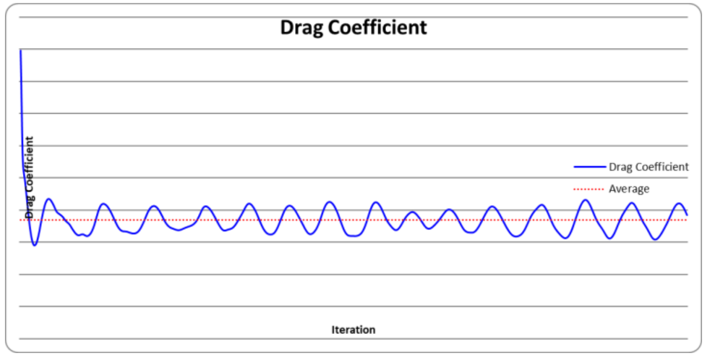


Airfoil mounted inside working section

Results – Validation

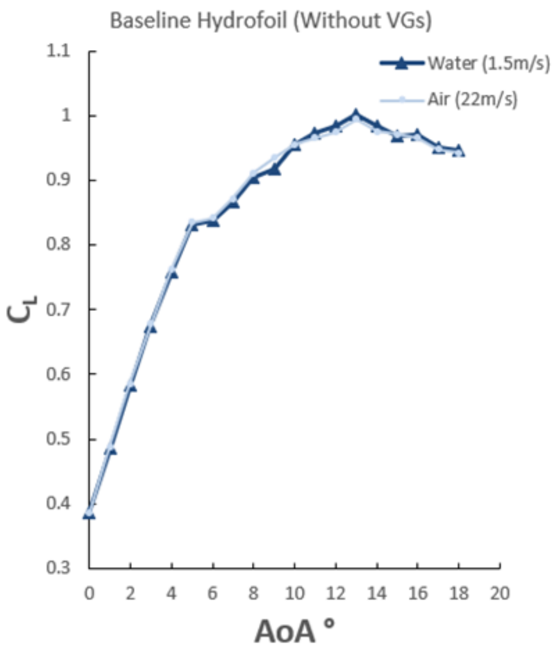


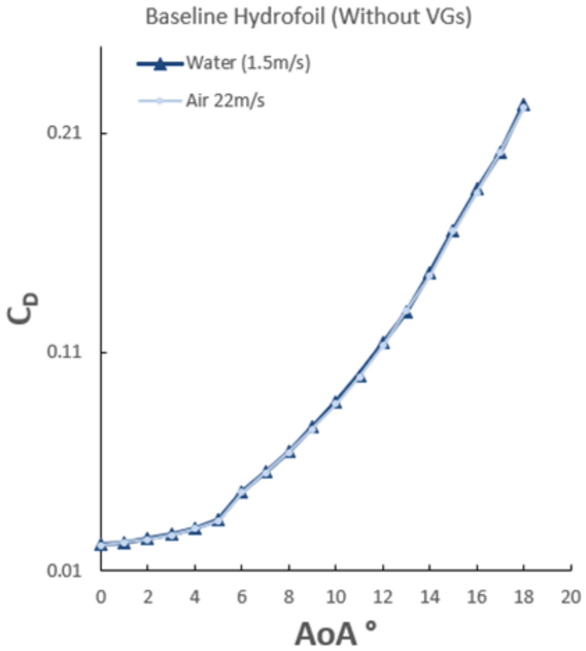


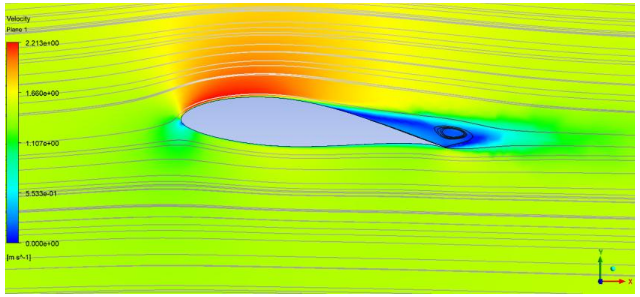


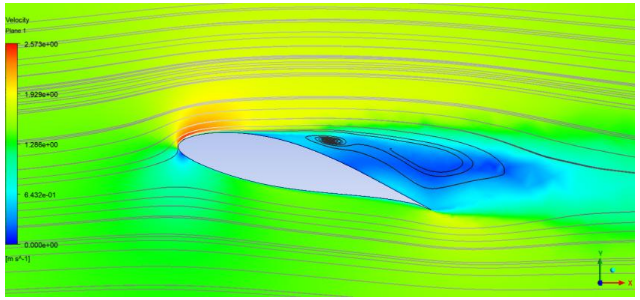
- The results from reference data for the NACA 63-618 airfoil was taken from a study by Pechlivanoglou et. al 2012 [8] at a Reynolds number of approximately 1.3×10^6.
- Direct comparison between the CFD simulations and XFOIL results.
- XFOIL data showed a clear and consistent rise in CL until it reaches an AoA of 10-12 degrees, after which it plateaus.
- The CFD results are taken as an average after 100 iterations, because of forced steady convergence by ANSYS Fluent.
- The reference results dataset at Re = 1.3×10^6 lies above both curves, with systematically higher CL values across the angle of attack range.

Results – CFD – Baseline



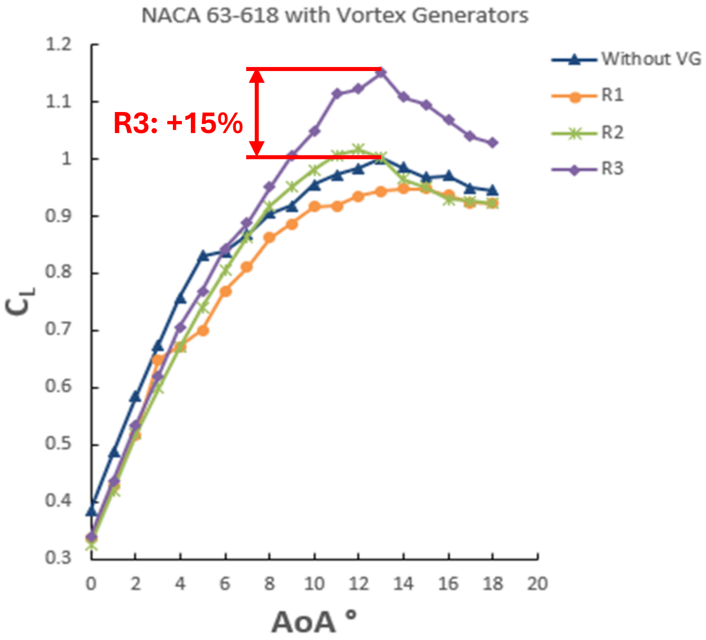


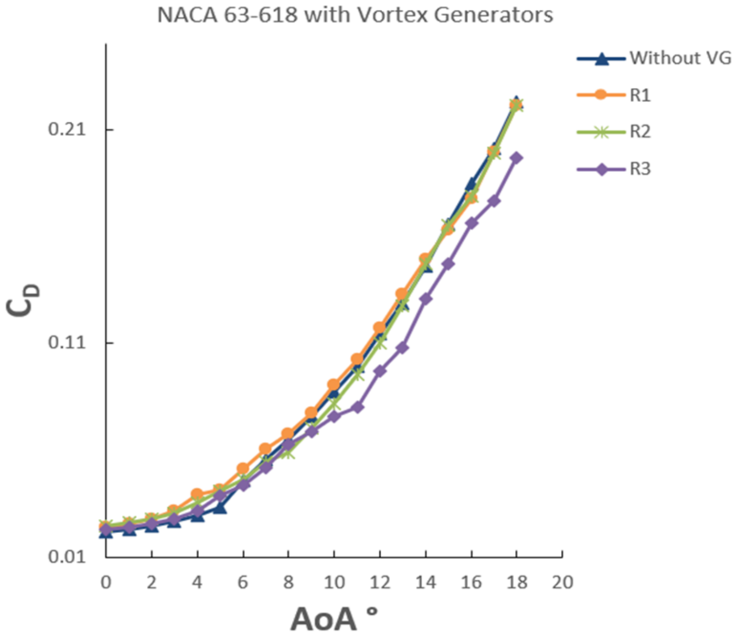


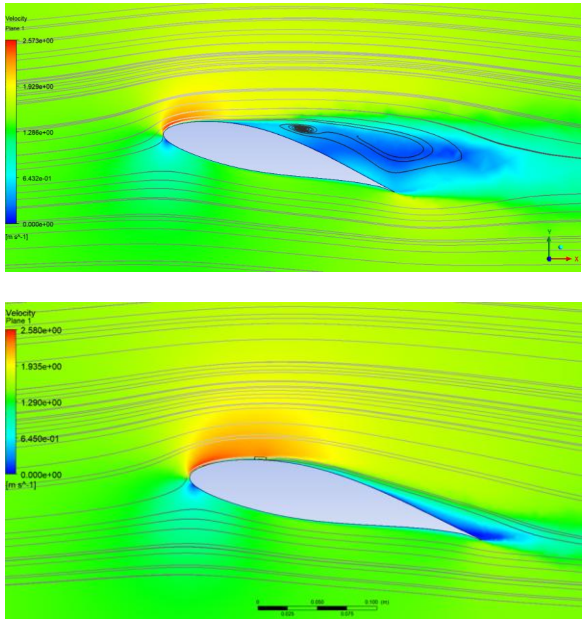


- The results of the air simulations were identical to those of the tidal case.
- At α=0°, the velocity distribution remained symmetric about the chord, with attached flow on both surfaces and only a small stagnation zone at the leading edge.
- At α=6° (Figure 23), the suction side experienced strong acceleration near the leading edge and only small regions of separation appeared near the trailing edge, while most of the boundary layer stayed attached.
- At α=12° (Figure 24), a large separation bubble formed on the suction side, extending well beyond mid-chord. This caused a breakdown in streamline attachment and the formation of recirculation zones, which are characteristic of post-stall behaviour.

Results – CFD – R series

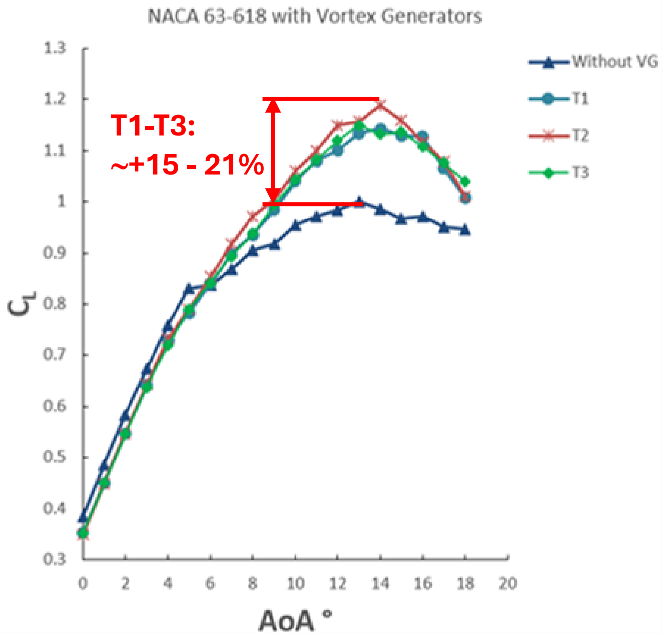


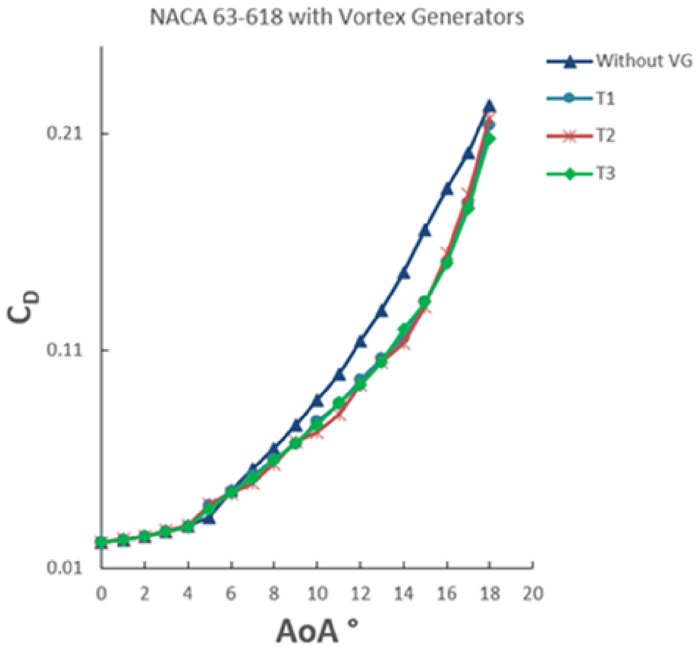


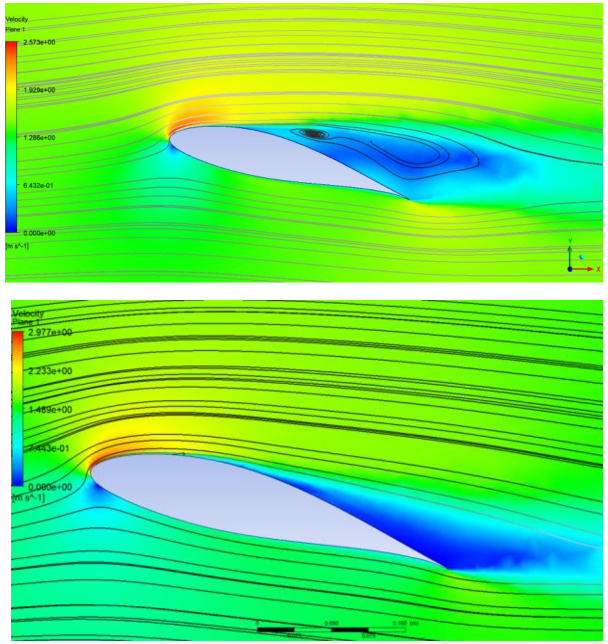


- R1 consistently showed poorer performance in terms of lift than baseline and incurring notably higher drag penalties , but showed good delay in stall.
- R2 displayed intermediate behaviour, producing average lift gains with drag levels remaining closer to those of the baseline hydrofoil
- R3 provided the most favourable performance, achieving a lift increase of approximately 15% along with a 10–12% reduction in drag at higher angles of attack.

Results – CFD - T series





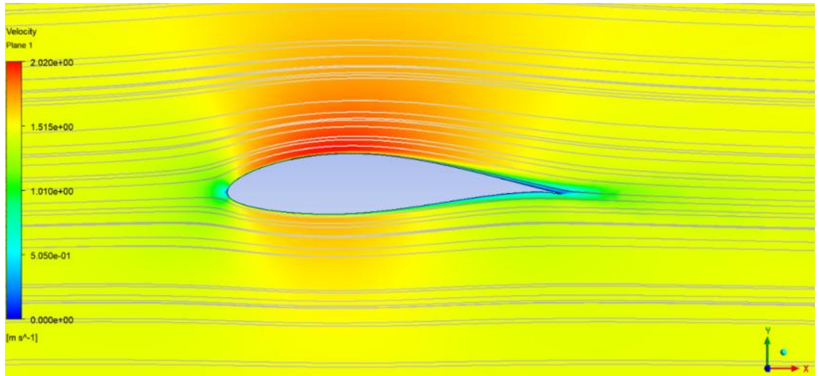


- All configurations of triangular vanes improved performance across the full range of angles of attack.
- T1 delivered small gains in lift but still managed to reduce drag compared with the clean hydrofoil case.
- T2 achieved the highest lift, reaching about 21% above the baseline, while also keeping drag low near stall, making it the best-performing configuration.
- T3 gave a more balanced result, with a 15% lift increase and the smallest drag growth at higher angles, showing that it is a reliable option.

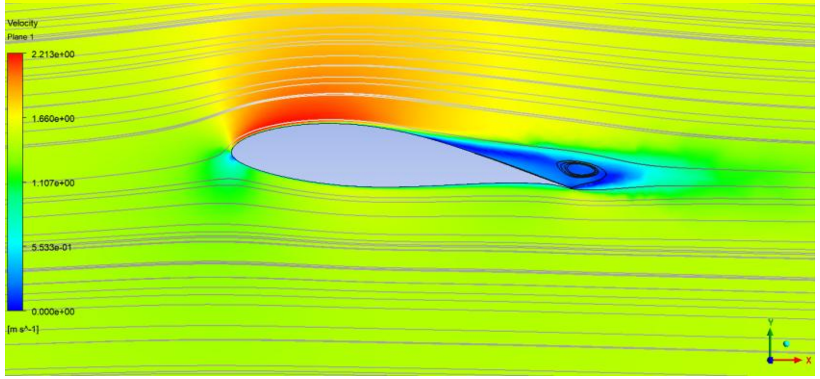
Results – CFD - Comparison

Baseline

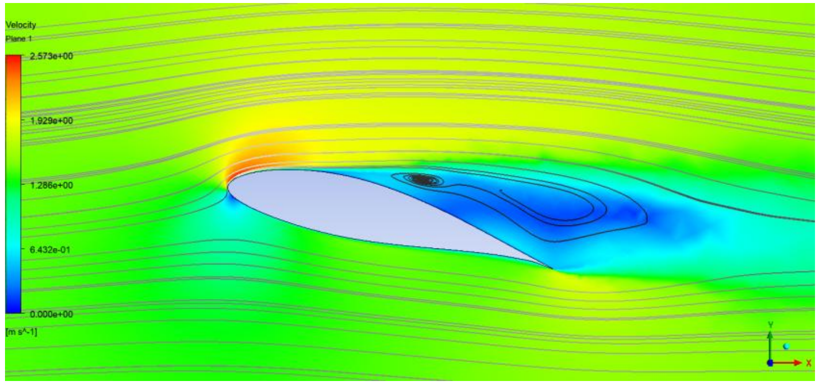
α = 0 °



α = 6 °

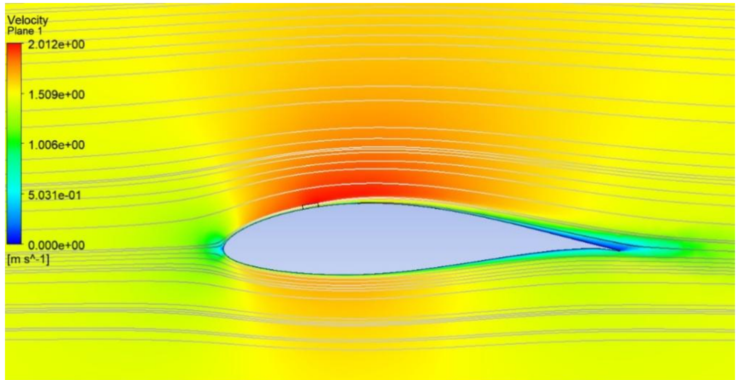


α = 12 °

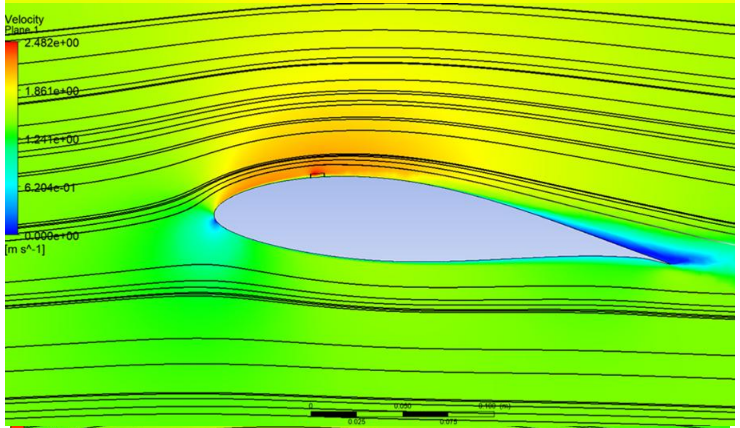


R3 (Best performing configuration)

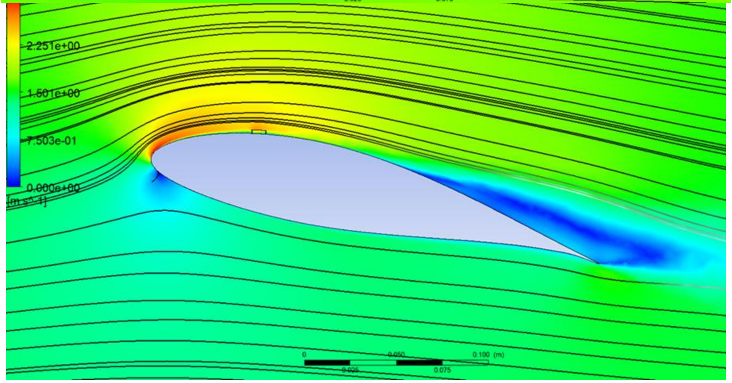
α = 0 °



α = 6 °



α = 15 °



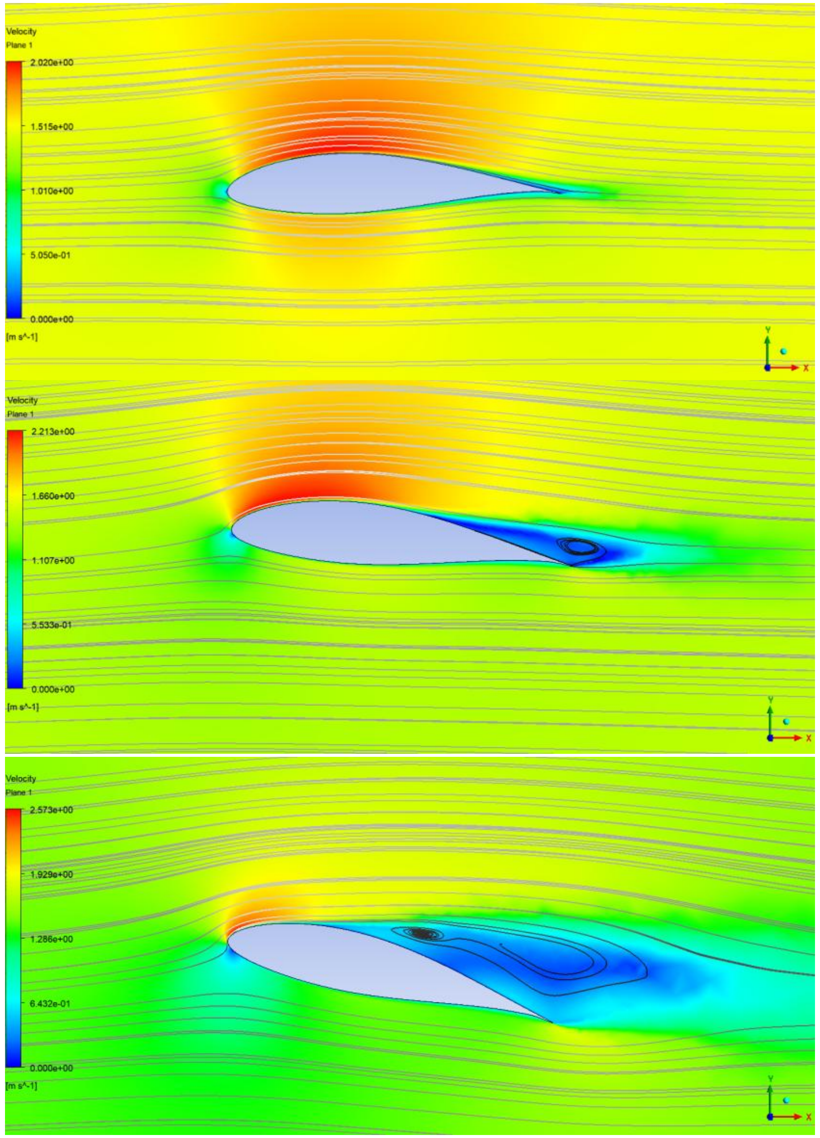
Results – CFD - Comparison

Baseline

α = 0 °

α = 6 °

α = 12 °

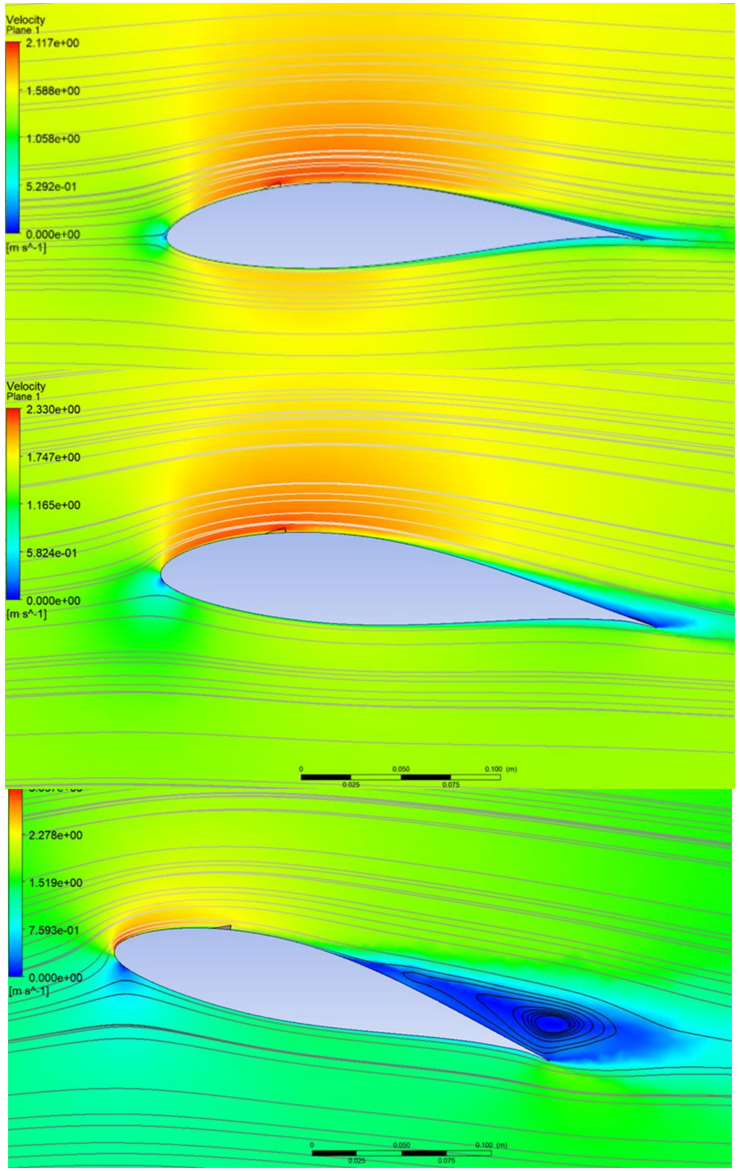


T2 (Best performing configuration)

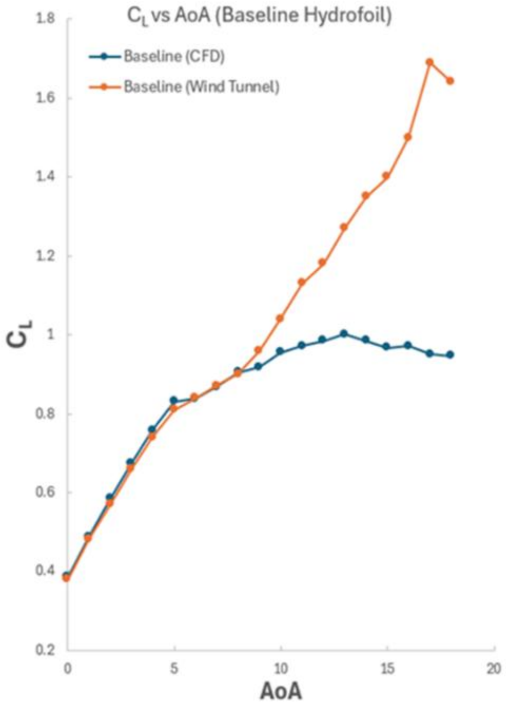
α = 0 °

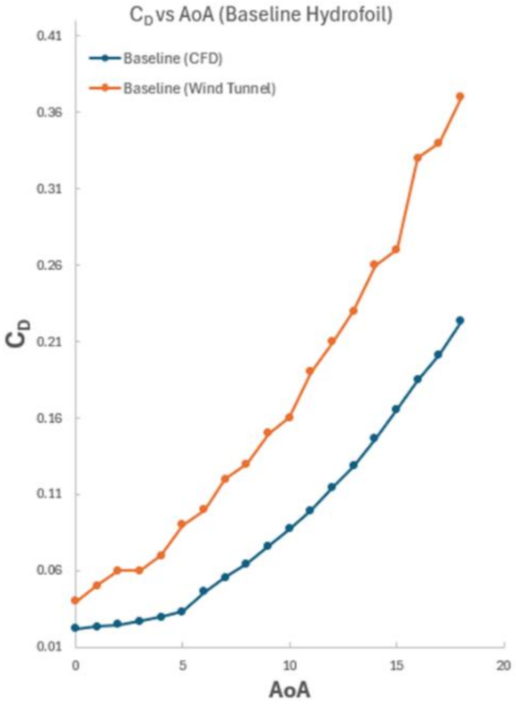
α = 6 °

α = 15 °



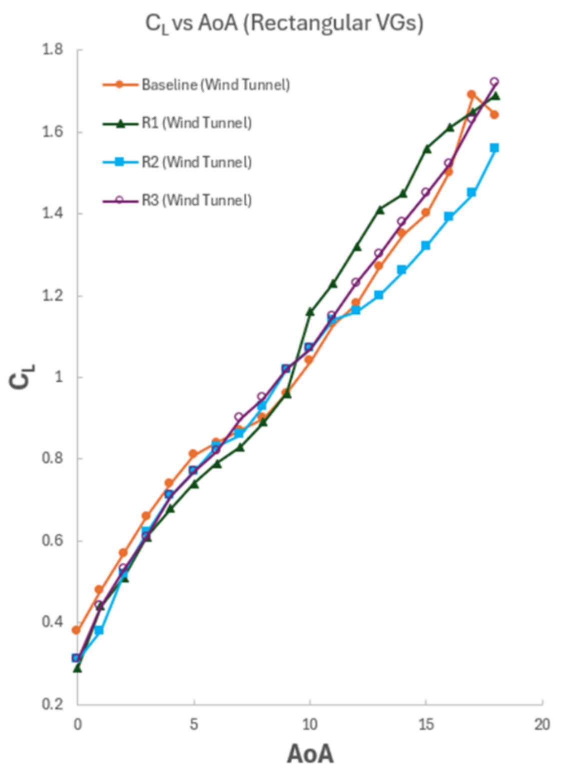
Results – Wind Tunnel – Baseline

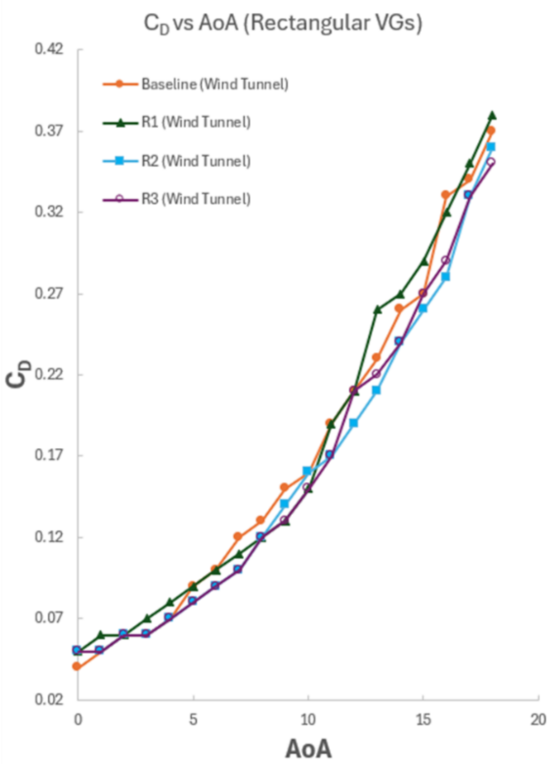




- Data followed almost identical trends up to approximately α≈8°, which indicated Reynolds-number similarity.
- Beyond this point the wind-tunnel measurements rise sharply while the CFD results remains comparatively flat displaying large divergence observed in the plots.

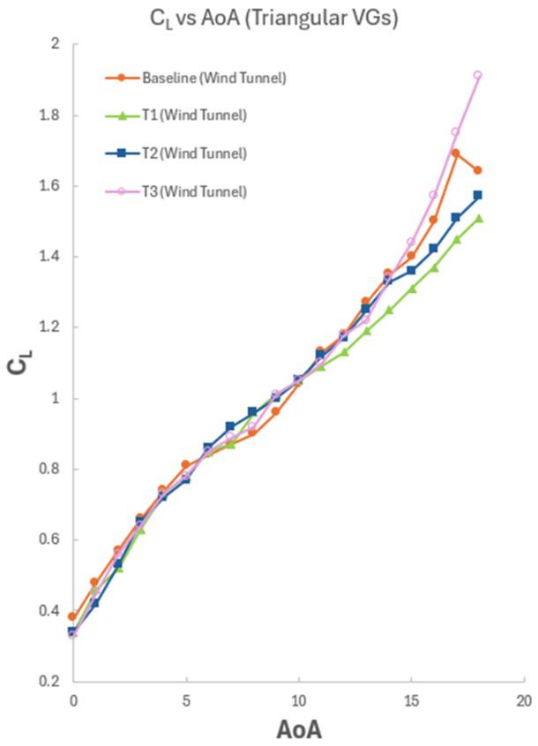
Results – Wind Tunnel – R series

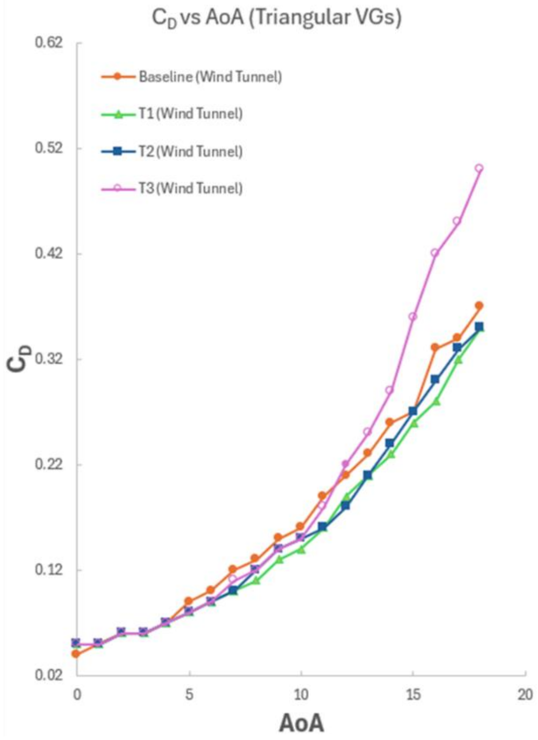




- R1, outperformed the baseline in the tunnel, delivered the smallest relative gains, particularly in the post-stall region. The stall was not captured in the wind tunnel experiments.
- R2 showed slightly lower improvements than baseline.
- R3 performed the best by reaching a C_L of 1.23 compared to 0.98 for the baseline (a 25% increase), while the CFD predicted only 1.12 (≈15% increase).

Results – Wind Tunnel – T series





- For the T1 setup at the highest angles of attack, around 12 to 14 degrees, the wind tunnel experiments recorded lift coefficients that went beyond 1.15 (15% increase).
- T2 configuration was the most effective among the triangular vane designs, producing the highest lift coefficient of approximately 1.18 at a 14° angle of attack (improvement of about 20% compared to the baseline performance).
- T3 showed the capacity to delay stall and the maximum lift coefficient values were highest at approximately 1.13 .

Conclusion

- Influence of passive vortex generators (VGs) on the hydrodynamic performance of the NACA 63-618 hydrofoil.
- The main aim was to assess whether vane-type VGs could provide practical benefits through separation control, lift enhancement, or drag reduction.
- The results show that adding vortex generators modifies the baseline aerodynamic behaviour in a clear and measurable way suggesting that passive VGs are a viable method of improving the performance of tidal turbine blades.
- Triangular vane series achieved the best performance by displaying a 15-20% increase in lift and significant reduction in drag.
- This improvement can be achieved either by incorporating vortex generators into the blade design during the development and testing stages or by adding them later as retrofit modifications to existing blades.

Recommendations

Recommendations for future work:

1. The size of the wind tunnel test section could be considered when designing future experiments, and the CFD domain could be modelled to match these dimensions more closely to reduce discrepancies.
2. Greater attention should be given to 3D printing and post-processing, as small surface distortions can alter the flow field and increase drag.
3. The reduction in lift and increase in drag observed in some cases may be linked to VG placement. Future studies can include VG placement iterations as a part in the investigation for optimal VG positioning and to maximise benefits.
4. Further research should also explore different VG shapes and sizes, including aerodynamic shapes of VGs, to determine configurations that deliver stronger performance improvements.

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THANK YOU