Aerodynamics and Flow Control Devices for Wind Turbines

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OUTLINE

1. Wind Europe Annual Statistics
2. Aerodynamic concepts
    - Airfoil designs
    - Airfoil profiles
    - Forces on an airfoil profile
    - Boundary layer
    - Pressure distribution
3. Flow Control Devices
    - Microtabs
    - Spoilers
    - Flexible Serrated Trailing Edge
    - Fences
    - Vortex Generators
4. Computational Fluid Dynamics (CFD): What is it and how it works?
5. CFD: Multiphase Flows: Eulerian and Lagrangian approach
    - Case study 1: Water droplets impingement in wind airfoil
    - Case study 2: Airfoil icing

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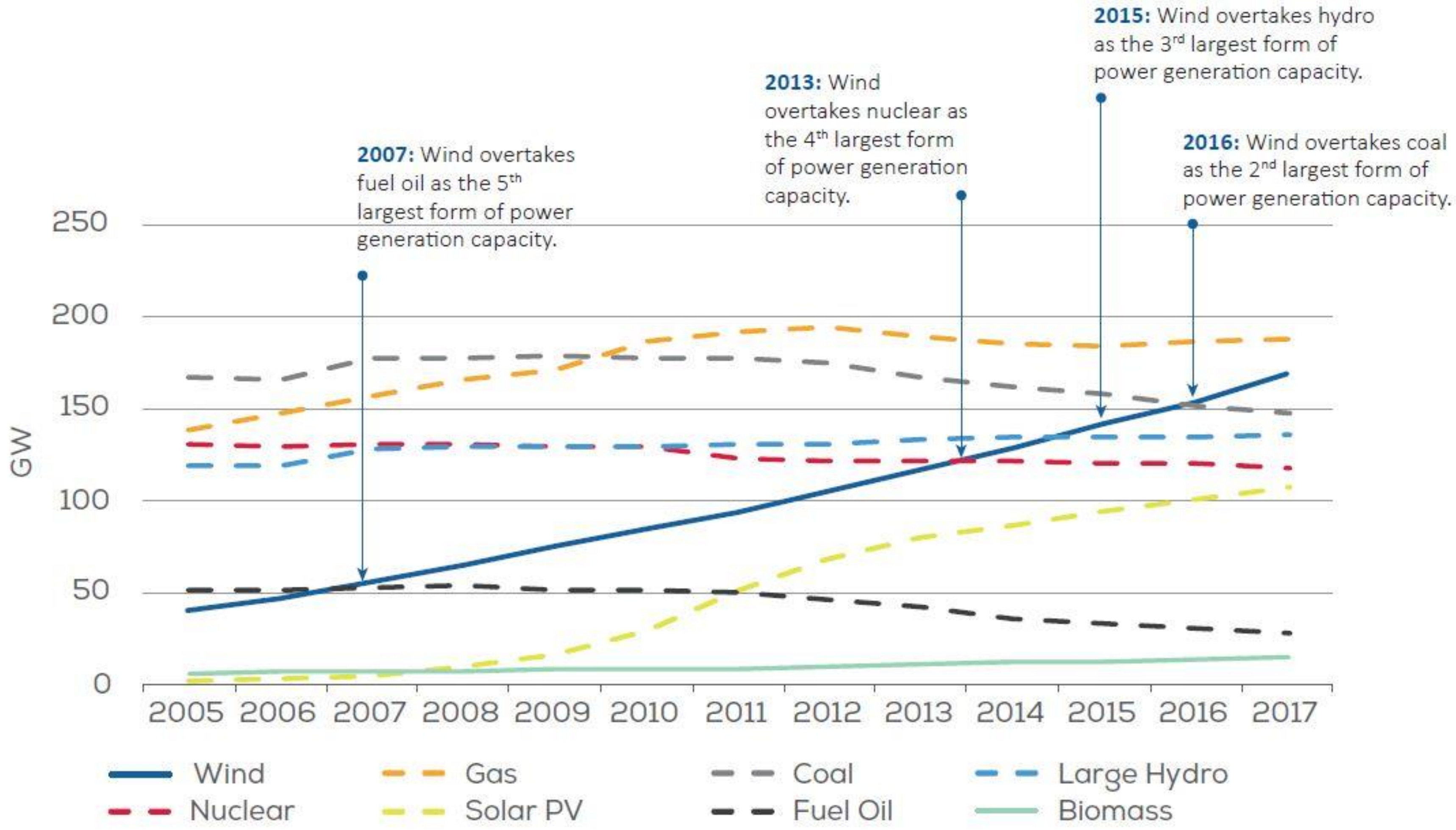
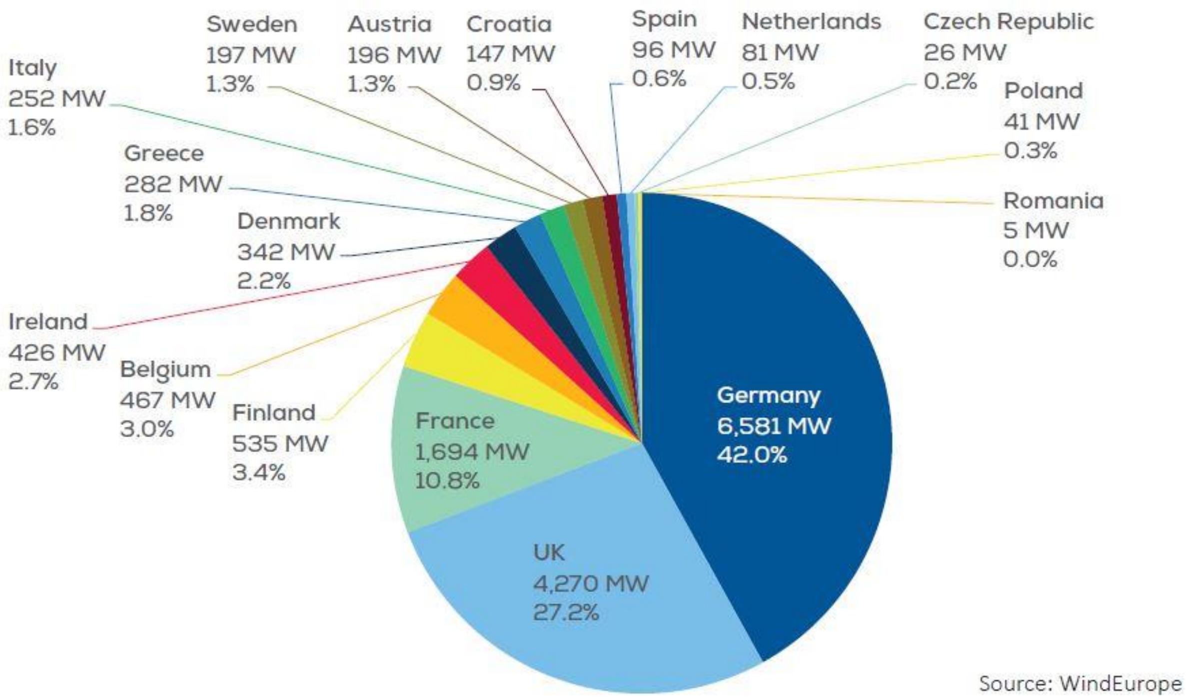
WIND POWER CAPACITY



Source: WindEurope

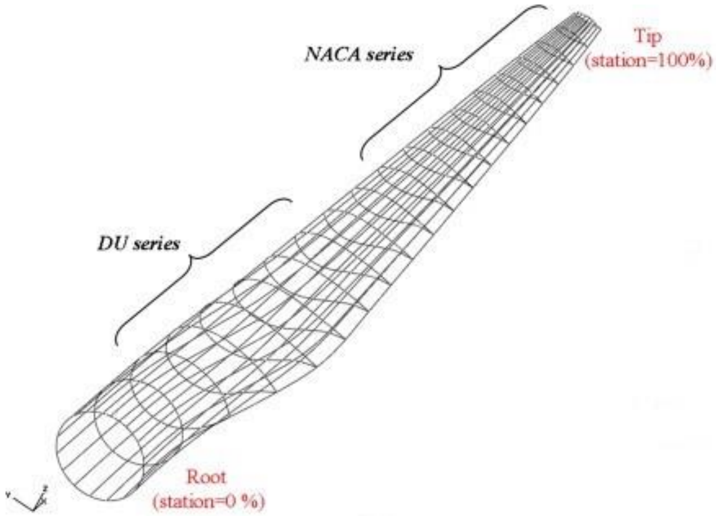
WIND POWER INSTALLATIONS

During 2017, 16.8 MW of wind power were installed across Europe.

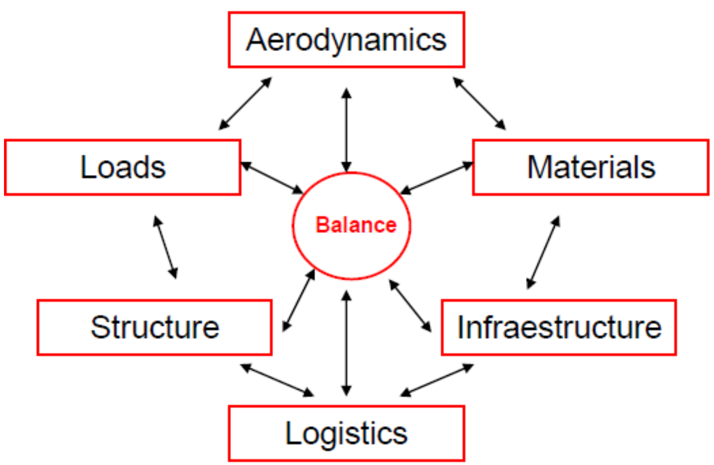


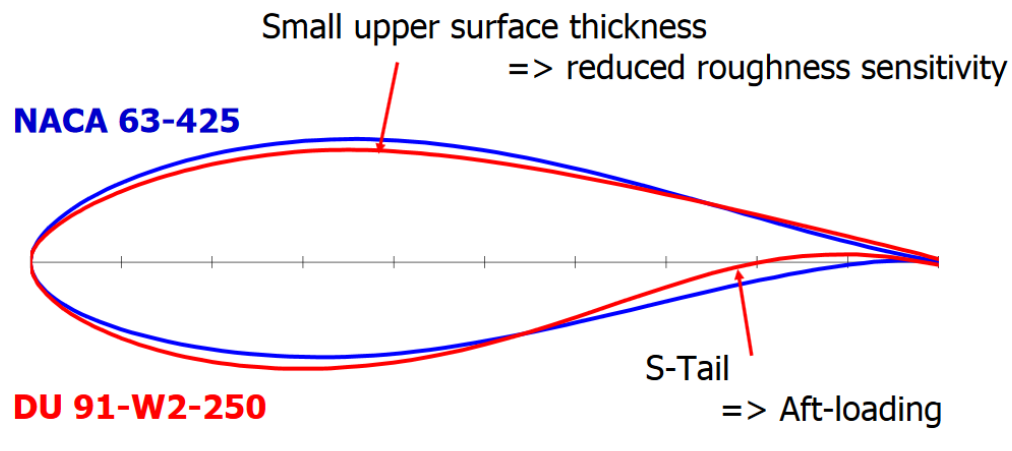
- Germany was the largest market in 2017
- UK presents five times more installations with respect to 2016
- Three countries had a record year in installations:
    - Finland (535MW)
    - Belgium (467 MW)
    - Ireland (426 MW)

AIRFOIL DESIGNS



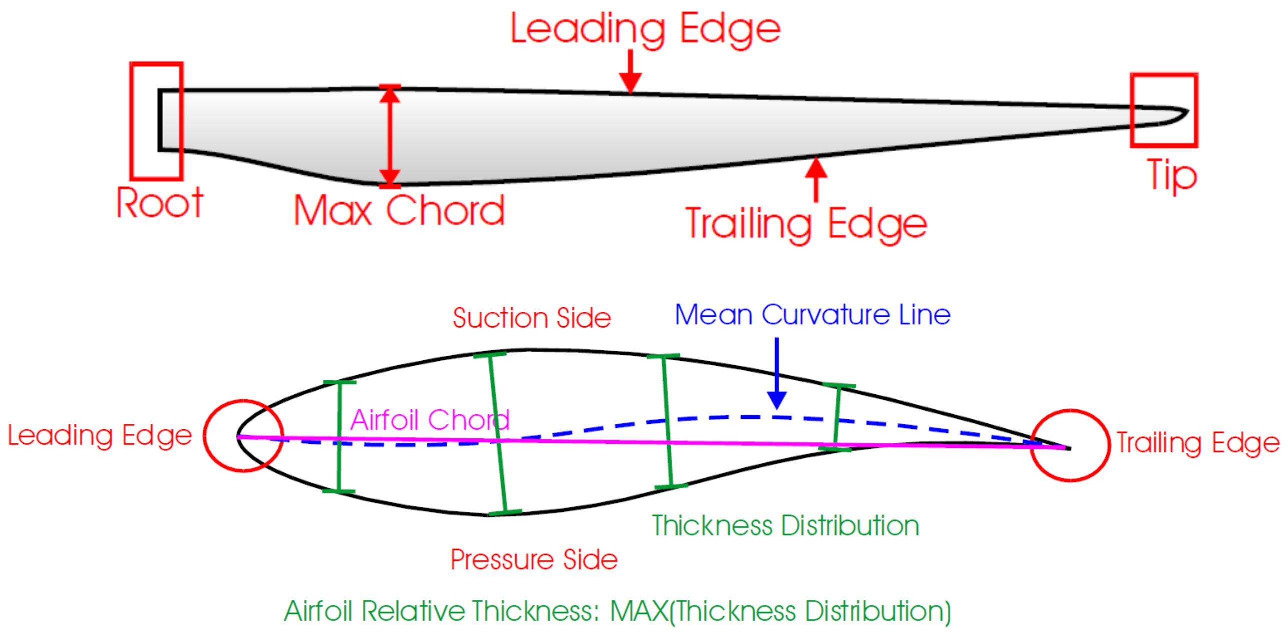
Airfoil series	
NACA	National Advisory Committe for Aeronautics
RISØ	Risø National Laboratory
NREL	National Renewable Energy Laboratory
DU	Delft University





Source: DUWIND, section Wind Energy, TUDelft

AIRFOIL PROFILE



Blade root: Area where the blade is attached to the hub to transfer the wind loads to the main shaft.

Blade Tip: The part of the blade that is the farthest from the hub.

Leading Edge: The part of the blade that hits first the wind in normal operation.

Trailing Edge: The end-knife edge part of the airfoil.

Chord: It refers to the imaginary straight line joining the Leading Edge and the Trailing Edge.

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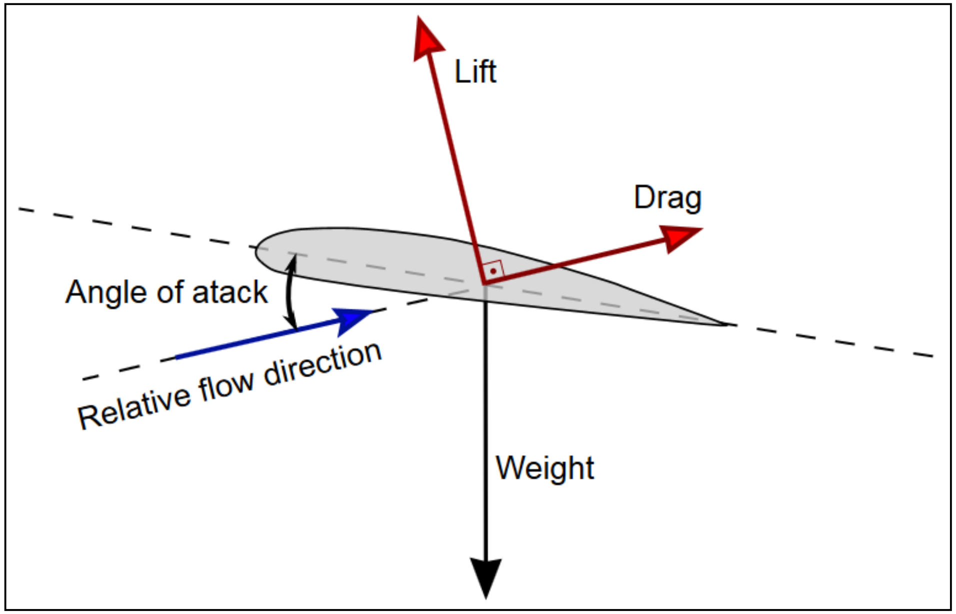
FORCES ON AIRFOIL PROFILE

The components of the resultant force acting on the profile are the **drag force** and **lift force**.



The drag force is due to the pressure and shear forces acting on the surface of the object.

The drag force acts in the direction of the motion of the fluid relative to the object.

$$C_d = \frac{D}{0.5 \cdot A \cdot \rho \cdot v^2}$$

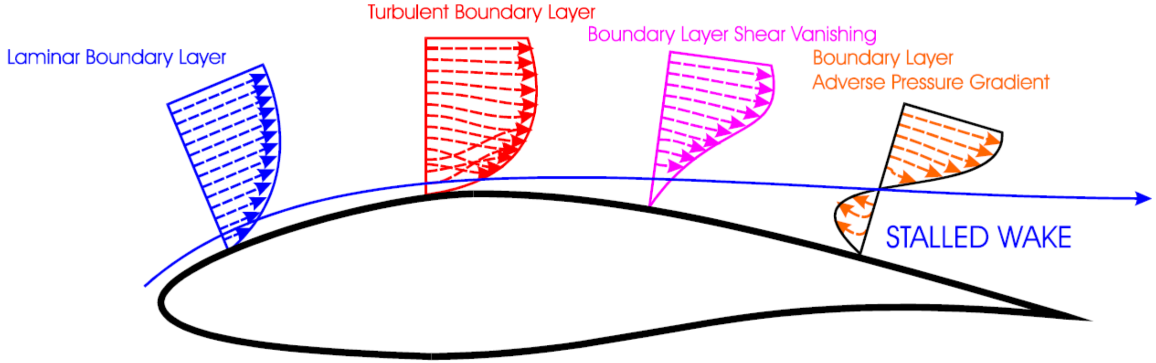
The lift force acts normal to the flow direction.

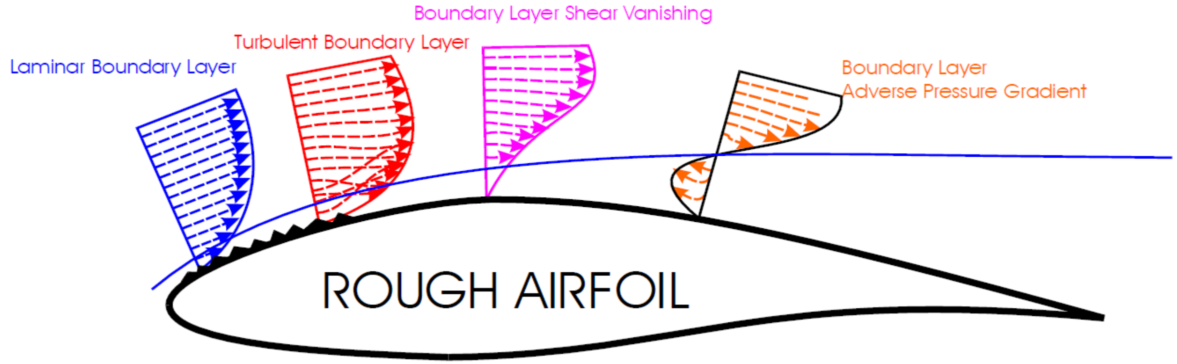
$$C_l = \frac{L}{0.5 \cdot A \cdot \rho \cdot v^2}$$

Both are influenced by the size and shape of the object and the Reynolds number of the flow.

$$\mathrm{Re} = \frac{inertial\ \ forces}{viscous\ \ forces} = \frac{\frac{\rho \cdot v^2}{L}}{\frac{\mu \cdot v}{L^2}} = \frac{\rho \cdot v \cdot L}{\mu}$$

BOUNDARY LAYER CONCEPT





Flows at high Reynolds numbers can be divided into two regions:

- A region where the viscosity is neglected.
- A very thin boundary layer at the wall where the viscosity must be taken into account.

The thickness of this layer increases from front to back, as increasing quantities of fluid become affected.

<u>Boundary layer separation</u>

Occurs when a portion of the boundary layer closest to the wall reverses in flow direction.

Exists in regions with adverse pressure gradients.

Ref: H. Schlichting, K. Gersten, "Boundary Layer Theory", Springer-Verlag Berlin Heidelberg, ISBN 978-3-662-52919-5, 9th Edition, 2017

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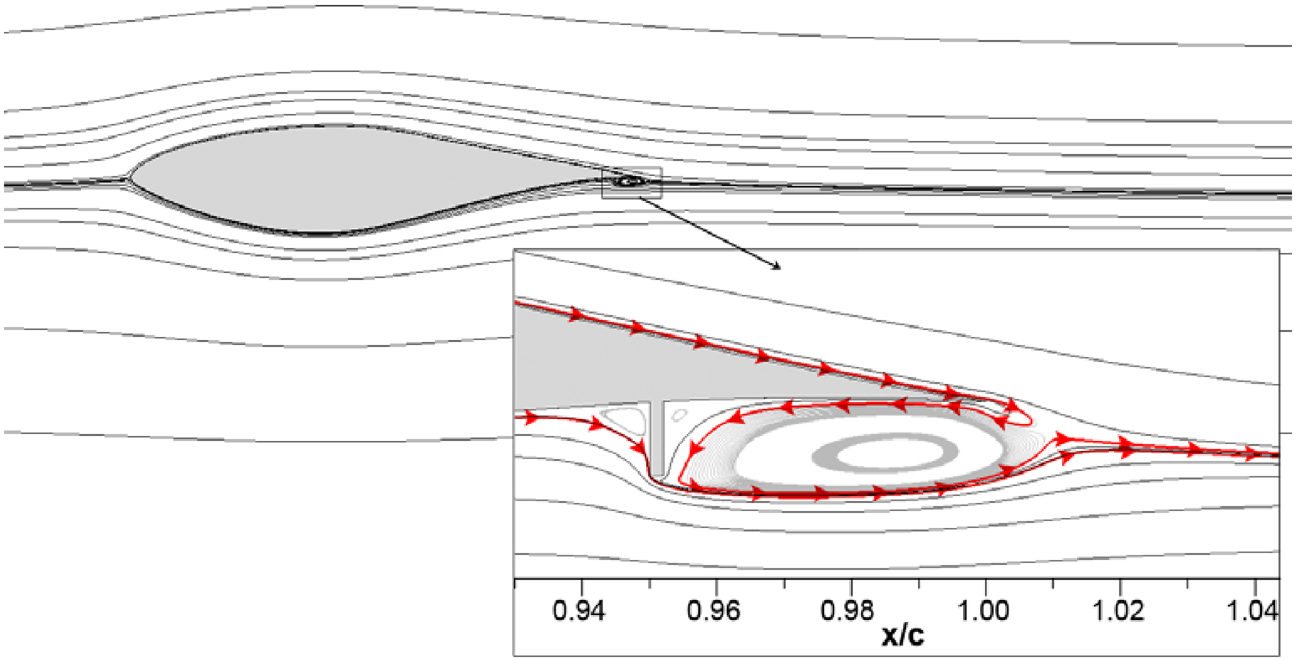
MICROTABS

Device for active load control applications.

- similar to Gurney
- Lift enhancement is achieved by deploying the tab on the pressure (lower) surface and lift mitigation is achieved by deploying the tab on the suction (upper) surface.



VIDEO 1

VIDEO 2

Ref: Scott et al. 2008 SANDIA Report Active Load Control Techniques for Wind Turbines

SPOILERS

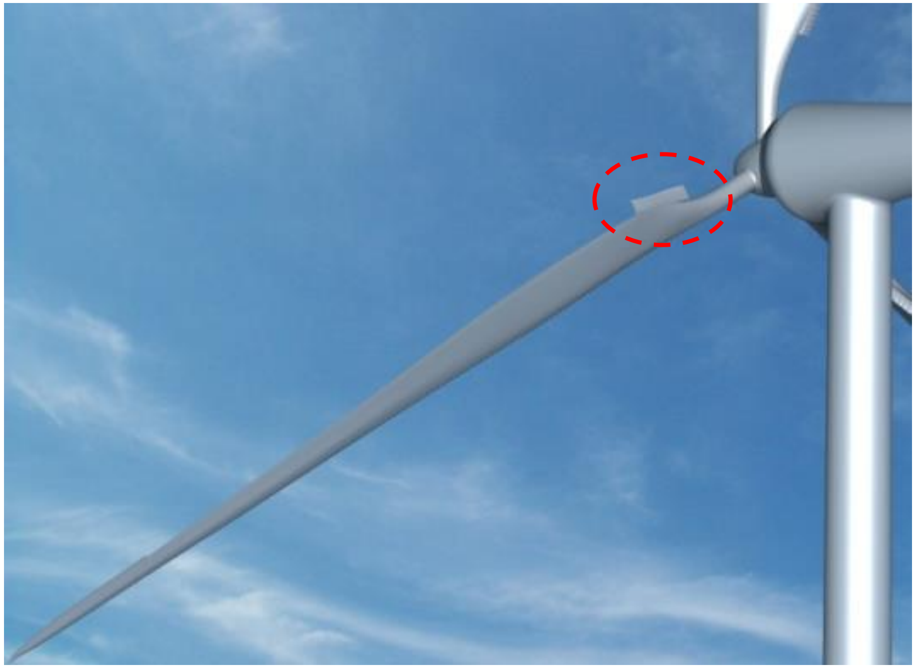
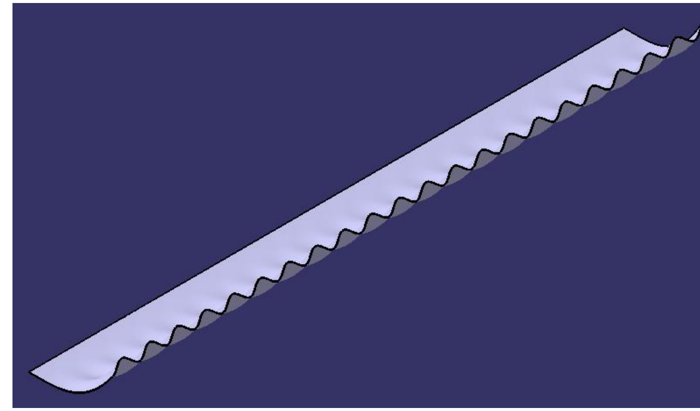
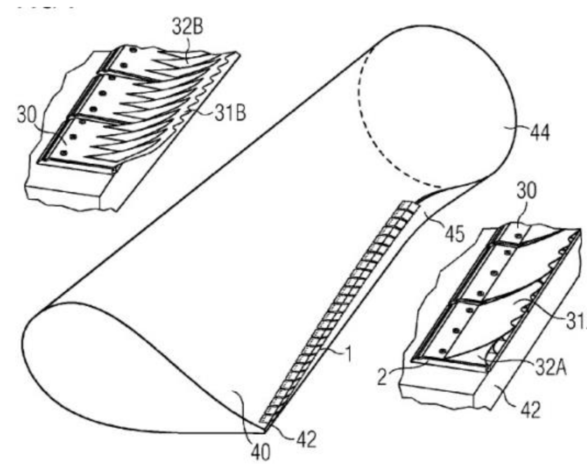


Fig. : Wind turbine blade having a spoiler with effective separation of airflow.



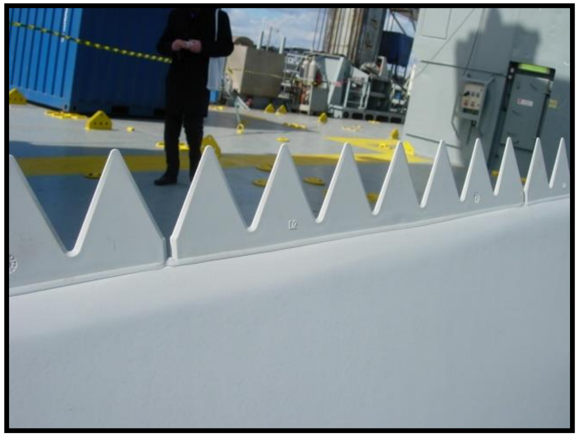


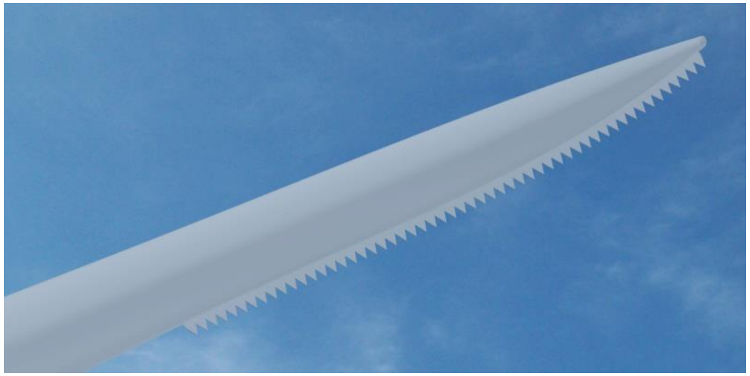
Ref.: LM GLASFIBER Patent: (EP 2 141 358 A1)

The root and the transition region, due to their section, do not help to the energy production of the wind turbine and even cause a drag increase

A spoiler is assembled in the inboard part of the blade and particularly to the transition region

FLEXIBLE SERRATED TRAILING EDGE





Ref.: Siemens Patent (Dino Tail) EP 1 314 885 B1

Wind turbine noise is one of the main issues for the widespread use of wind energy:

1. Airfoil self-noise
2. Inflow-turbulence noise

The shedding of the wake and the confluence of flow from the pressure and suction sides of the profile are sources of aerodynamic noise (increase in drag and a reduction in lift).

This noise can be reduced by modifying the TE geometry

→ Flexible serrated trailing edge, also known as Dino Tail, patented by Siemens

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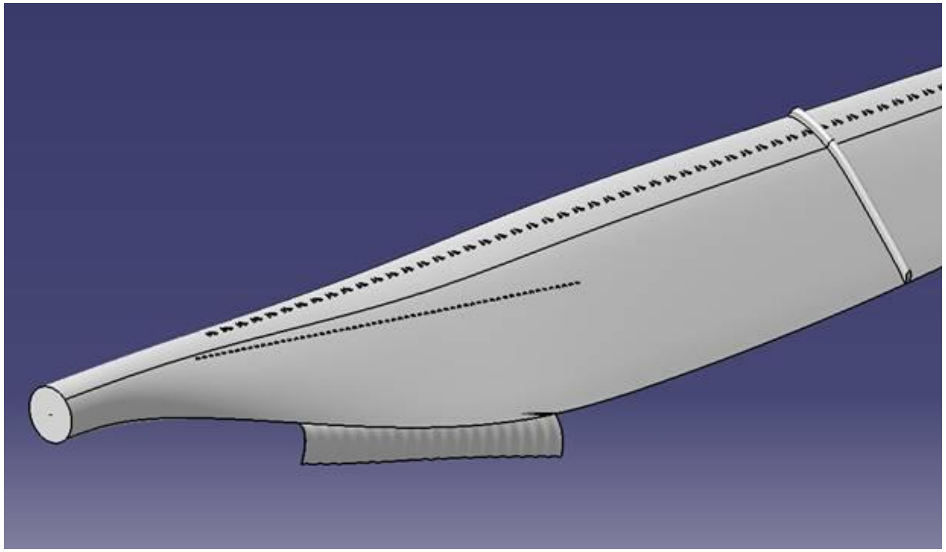
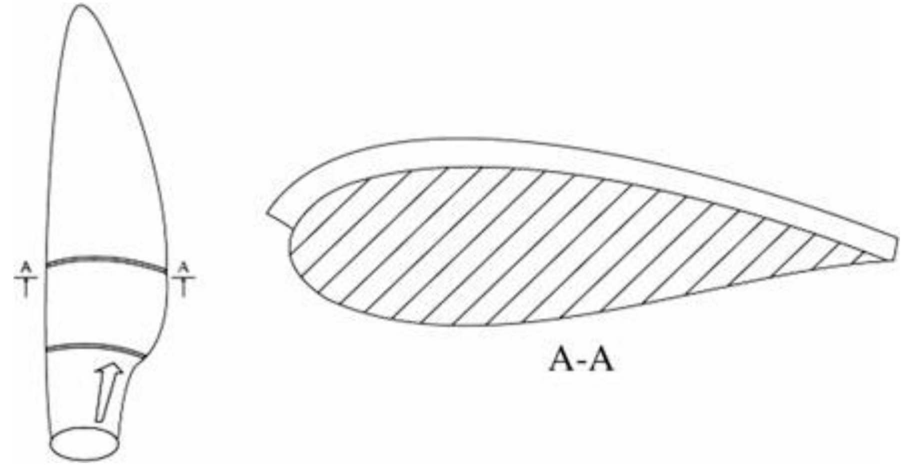
FENCES





Ref: SIEMENS PATENT US20120051936 A1

Device They consist of fin-like vertical surfaces attached to the upper surfaces of the wing that are used to control the airflow.

Problem This airflow generates adverse consequences in wind turbine performance, particularly because it contributes to the separation of the main airflow of the blade surface, and therefore, reduce the rotor blade lift

Function Disrupt the spanwise airflow, protecting the outboard wing section from a developing inboard stall

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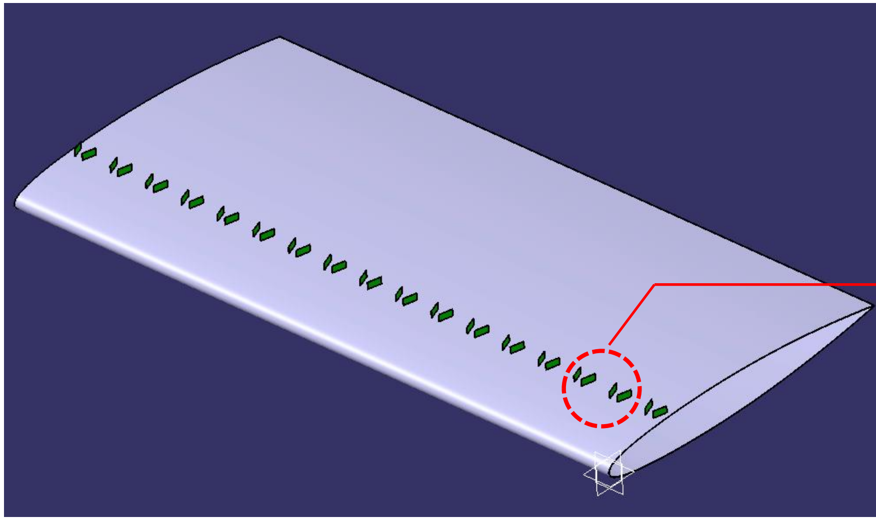
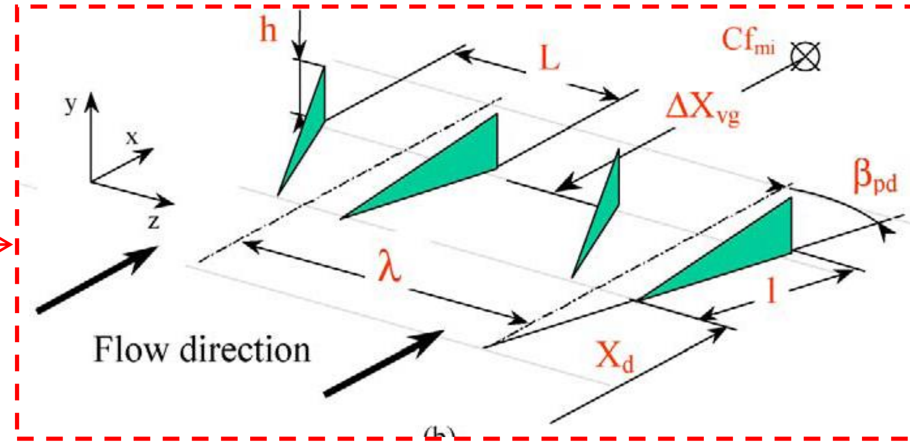
VORTEX GENERATORS





Device A Vortex Generator (VG) is a passive flow control device which modifies the boundary layer fluid motion bringing momentum from the outer flow region into the inner flow region of the wall bounded flow.

Geometry Triangular or rectangular vanes. Dimensioned to the local boundary layer thickness, inclined at an angle to the incoming flow and placed as close as possible of the leading edge in cascades in groups of two.

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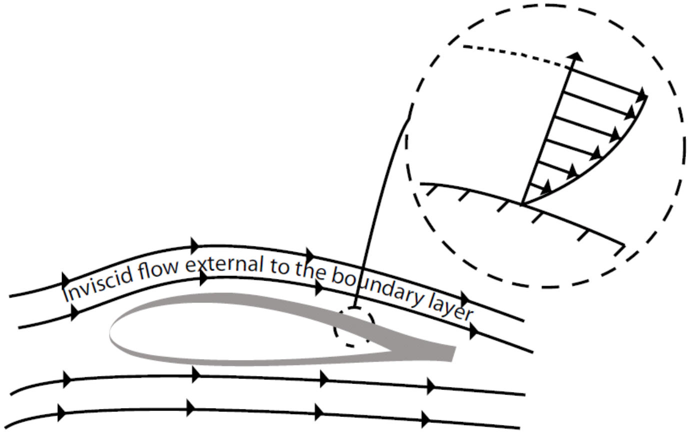
Ref: Aramendia, I; Fernandez-Gamiz, U; Ramos-Hernanz, J; Sancho, J; Lopez-Guede, J.M; Zulueta, E. Flow Control Devices for Wind Turbines. In Energy Harvesting and Energy Efficiency: Technology, Methods and Applications; Bizon, N., Mahdavi Tabatabaei, N., Blaabjerg, F., Kurt, E., Eds.; Springer International Publishing, 2017, pp. 629-655.

VORTEX GENERATORS



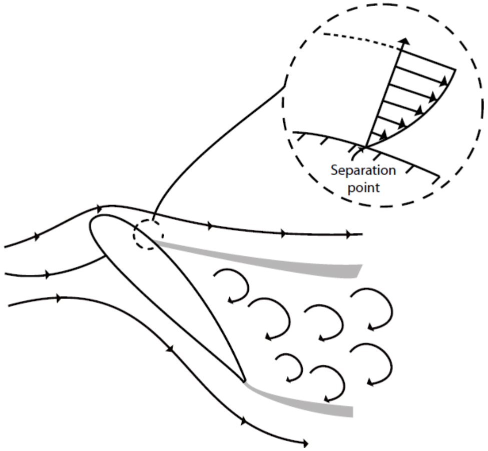
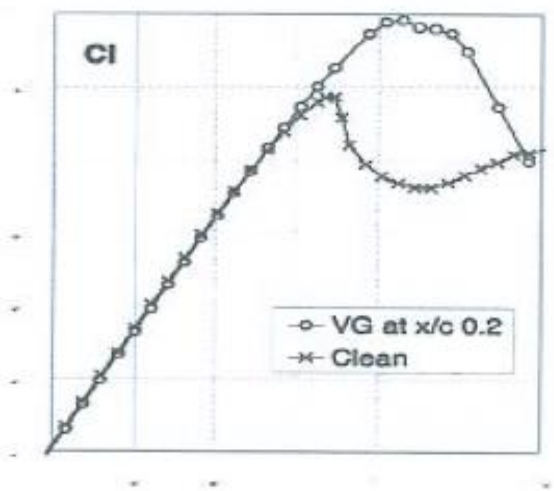


Figure 4: (a)Flow across an airfoil. (b) Separated flow over the top surface of an airfoil



Main function:

•Delay or prevent separation of the flow.

•Generation of longitudinal vortices

•Overturn of the BL flow via large scale motions.

• Bringing high momentum fluid down into the near wall region of the boundary layer.

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Ref: van Rooij R. P. J. O. M. and Timmer W A "Roughness Sensitivity Considerations for Thick Rotor Blade Airfoils". AIAA-paper 2003-0350.

ADVERSE ATMOSPHERIC CONDITIONS

Surface contamination

Erosion

Rain

Ice accretion

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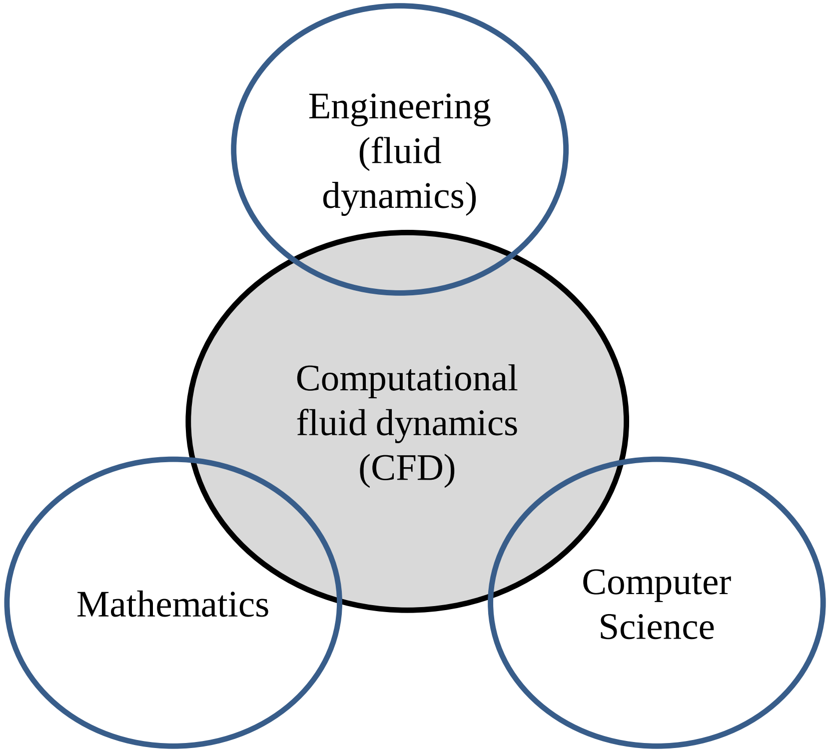
COMPUTATIONAL FLUID DYNAMICS (CFD)



Two fundamental approaches to design and analyze engineering systems that involve fluid flow

Experimentation
Calculation
Validation

CFD techniques allow alternative designs to be evaluated over a range of dimensionless parameters that may include the Reynolds number, Mach number or flow orientation for instance.

Commercial codes
- ANSYS (Fluent)
- SIEMENS (Star-CCM+)

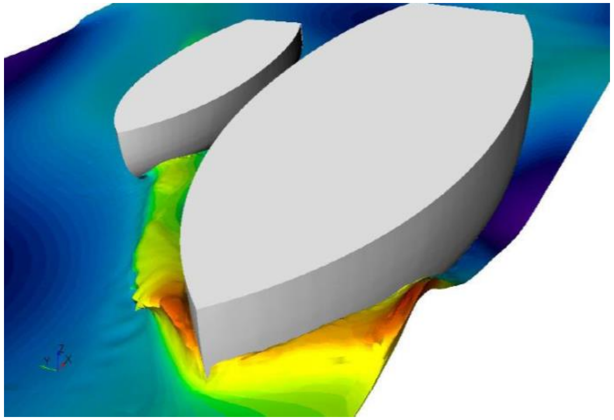
Open Source codes
- OPENFOAM
- SU2

CFD: MULTIPHASE FLOWS

MULTIPHASE FLOWS

STRATIFIED FLOWS

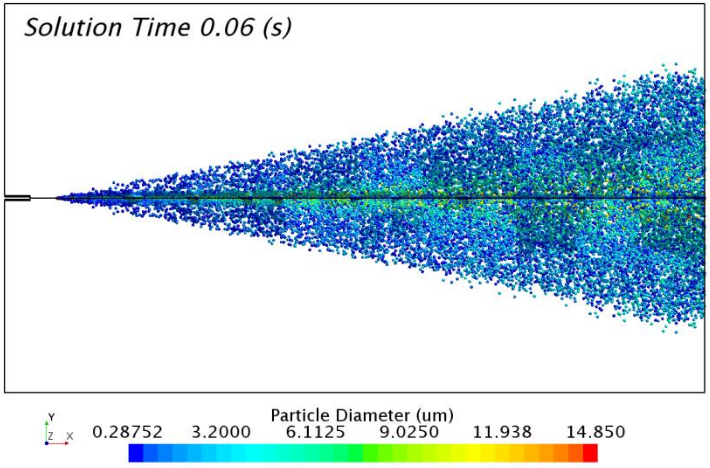
Free surface flows such as waves around hulls, annular flows in pipes)



DISPERSED FLOWS

Flows with bubbles, droplets and particles

More suited to simulate the impact of adverse atmospheric conditions on airfoils (rain conditions)



Ref: I. Aramendia, U. Fernandez-Gamiz, A. Lopez-Arraiza, C. Rey-Santano, V. Mielgo, F.J. Basterretxea and M.A. Solaetxe "Experimental and Numerical Modeling of Aerosol Delivery for Preterm Infants". Int. J. Environ. Res. Public Health, 2018, 15, 423

CFD: MULTIPHASE FLOWS

DISPERSED FLOWS

LAGRANGIAN MODEL

When it is necessary to track the movement of individual particles in fine detail.

Solves the trajectories of each particle.

Suited for multiphase flows where the discrete phase is well represented by small particles (Spray injections, aerosols, dust dispersion)

EULERIAN MODEL

When the fine details of the particle are not needed.

Consider the particles in terms of concentration (volume fraction) and averaged velocity.

More economical than the LMP

Suited to flows where each phase can be considered continuously mixed (a cloud sand that is transported by wind, bubbles moving inside liquids)

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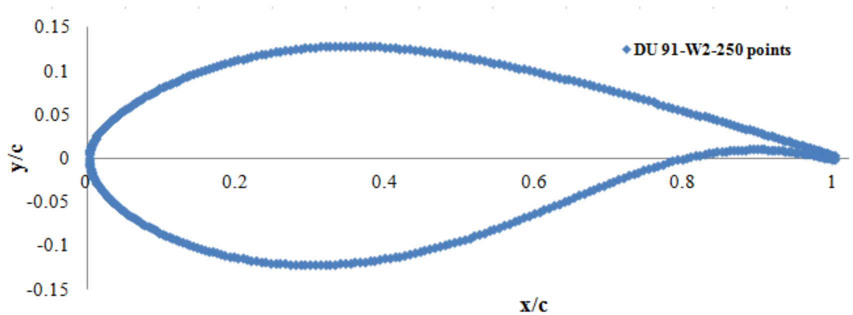
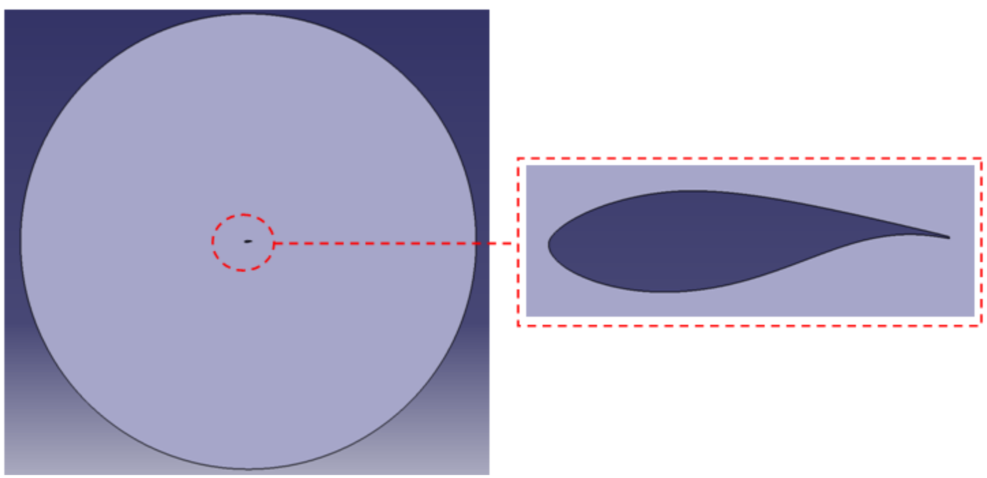
CASE STUDY 1: WATER DROPLETS IN WIND AIRFOIL

GEOMETRY



Import points to CAD software (CATIA V5)

- Generate the desired region for CFD analysis



DU 91-W2-250 (Coordinates)	
x/c	y/c
1	0.002131
0.9966	0.003137
0.99314	0.004139
0.98961	0.005151
0.98601	0.006171
….	….
0.98601	0.000432
0.98961	-0.00022
0.99314	-0.00086
0.9966	-0.00149
1	-0.00213

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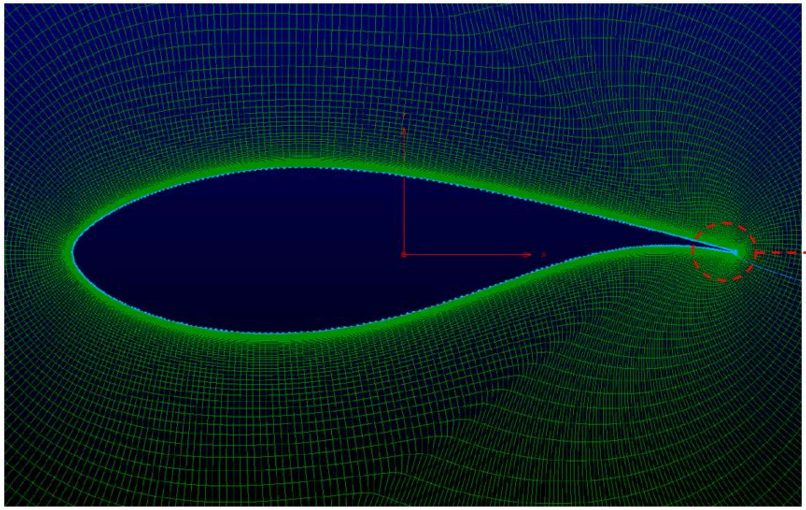
CASE STUDY 1: WATER DROPLETS IN WIND AIRFOIL

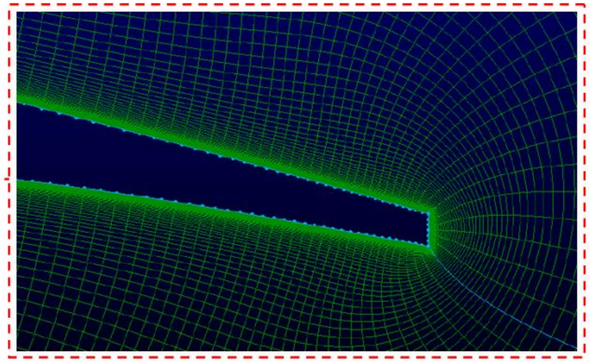
MESH GENERATION

The mesh generation is where you have the most direct influence on how fast, how converged and how accurate your CFD solutions are.

Generated with the software **Pointwise** (208.624 cells)

→ Structured mesh → Advantages → Alignment: CFD solvers converge better and can produce more accurate results when the grid is aligned with the predominant flow direction





CASE STUDY 1: WATER DROPLETS IN WIND AIRFOIL

MODELING THE EXTERNAL AIRFLOW AND WATER PARTICLES (PROCEDURE)

Lagrangian Multiphase model (LMP)

Air → The single-phase flow (air)

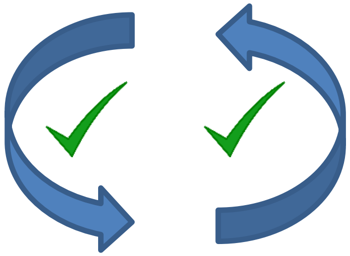
- Unsteady airflow ($\Delta t = 0.001s$)
- Ideal gas
- Turbulent gas (K-Epsilon model)
- Gravity

↓

Initial Condition

↓

Two-way coupled



Water droplets →

- Define the Injectors
- Define the Lagrangian phases
- Define the Fluid Film
- Define the Multiphase Interaction

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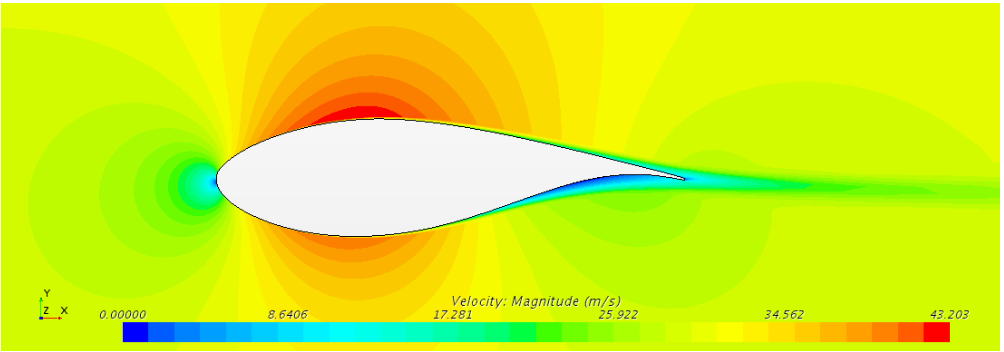
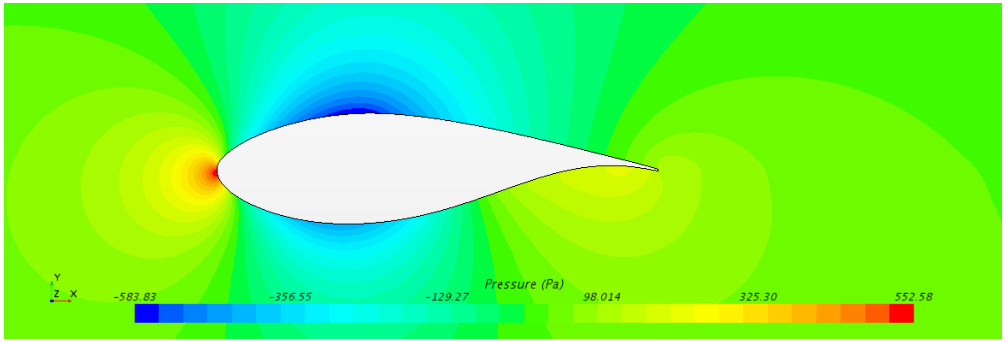
CASE STUDY 1: WATER DROPLETS IN WIND AIRFOIL

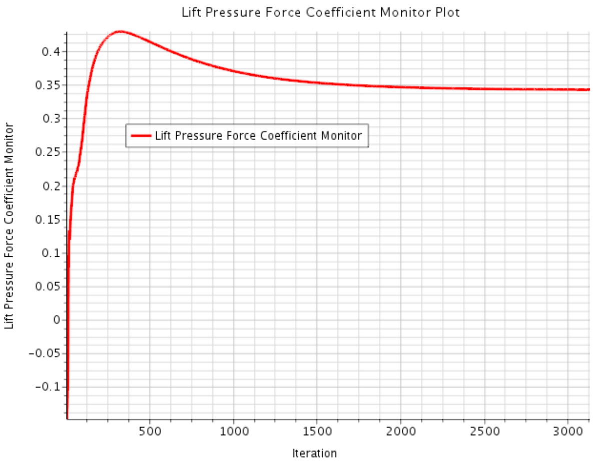
MODELING THE EXTERNAL AIRFLOW

Airflow velocity magnitude (m/s)



Airflow pressure (Pa)





C_L= 0.3423 (AoA = 0º)

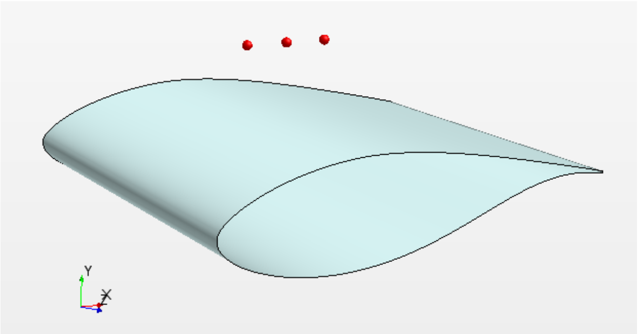
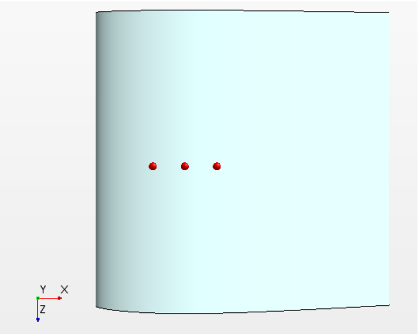
C_D= 0.0145 (AoA = 0º)

CASE STUDY 1: WATER DROPLETS IN WIND AIRFOIL

MODELING THE WATER PARTICLES

Injectors

- Solid Cone type
  - Outer Cone Angle: 30º
  - Mass Flow Rate: 0.01 kg/s
  - Droplet Diameter: 0.3 mm
  - Velocity Magnitude: 30 m/s

Lagrangian phases

Injected Particles

Stripped Particles

- Material Particles (Spherical particles)
- Liquid (H_2O) – Constant Density
- Pressure Gradient Force
- Drag Force
- Two-way Coupling
- Bai-Gosman Wall Impingement

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CASE STUDY 1: WATER DROPLETS IN WIND AIRFOIL

MODELING THE FLUID FILM AND MULTIPHASE INTERACTIONS

Lagrangian phase (Injected Particles)

Fluid Film phase

→ Impingement

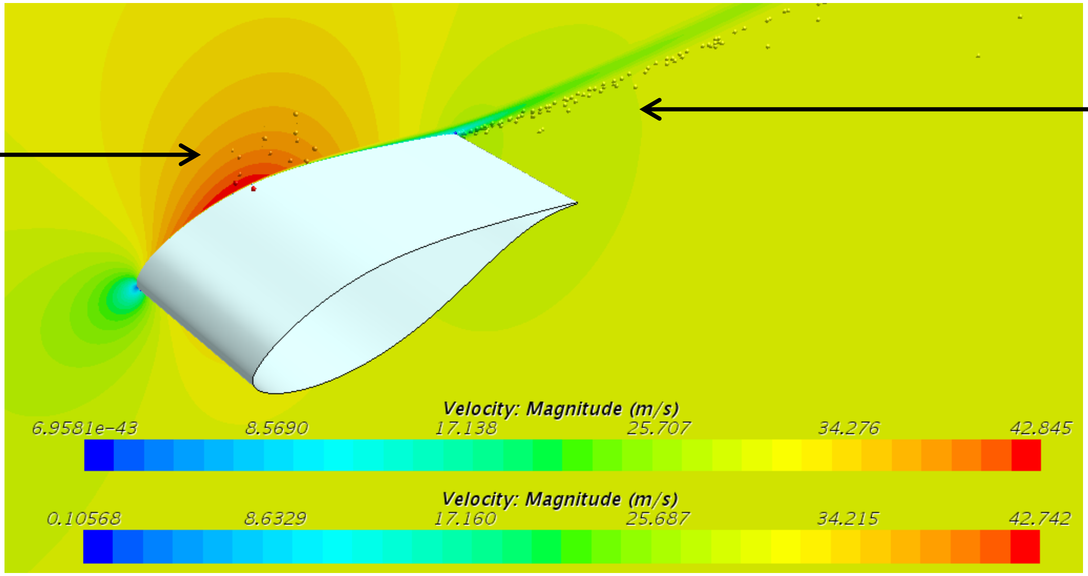
Fluid Film phase

Lagrangian phase (Stripped Particles)

→ Wave Stripping

Edge Stripping

Injected water droplets

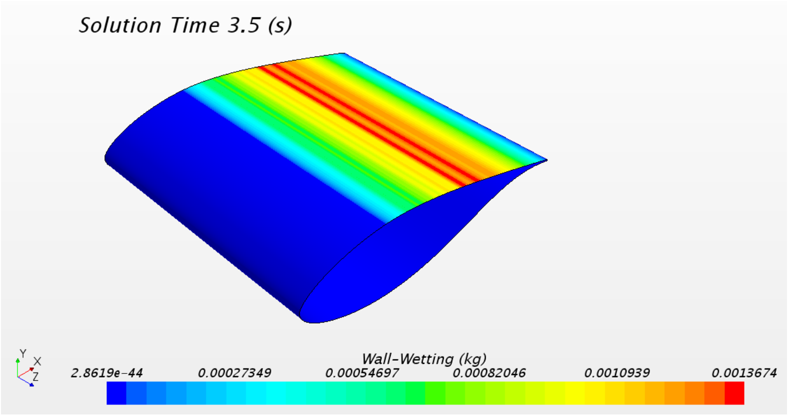


Stripped water droplets

CASE STUDY 1: WATER DROPLETS IN WIND AIRFOIL

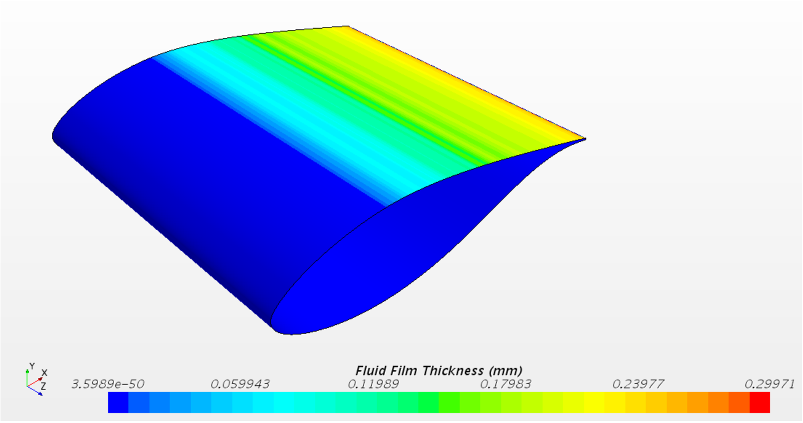
MODELING THE FLUID FILM AND MULTIPHASE INTERACTIONS

Wall-Wetting



Injected particles impinge the airfoil. Wall-wetting indicates the amount of mass accumulated in the fluid film over time

Fluid Film Thickness



The fluid film is formed over the airfoil surface. Water droplets can stripped of the airfoil due to waves instabilites or once they reach the trailing edge

CASE STUDY 2: AIRFOIL ICING

When aircraft pass through air containing supercooled liquid water droplets, it is possible for the droplets to impact the aircraft surface and form layers of ice.

Ice formation on an airfoil changes the aerodynamic properties of the blade, and leads to:

1. Loss of lift
2. Increase in drag
3. Changes in pressure distribution

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CASE STUDY 2: AIRFOIL ICING

HOW TO SETUP AN ICE ACCRETION CASE?

1. Modelling the External Airflow
2. Modelling the Supercooled Droplets

} **Dispersed Multiphase model (DMP)**

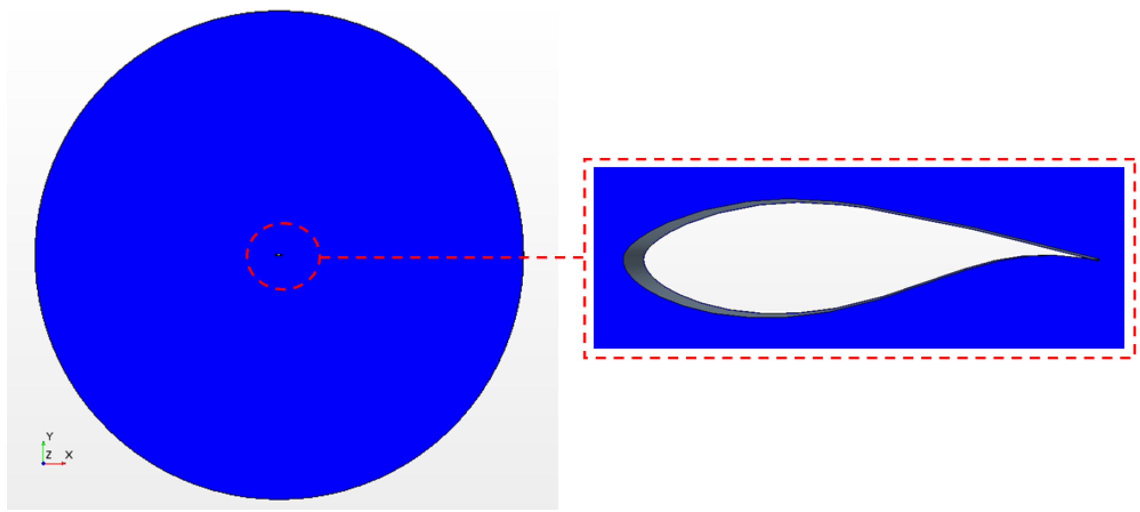
3. Modelling the Impingement and formation of a fluid film
4. Modelling the Solidification of liquid water into solid ice
5. Modelling Mass removal from surfaces (Optional)

} **Fluid Film and Multiphase Interactions**

GEOMETRY

Aerodynamic profile

DU91 W2 250



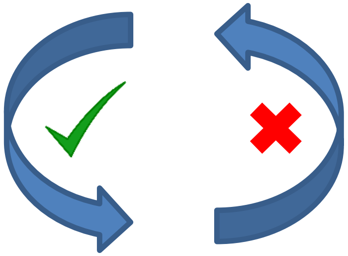
CASE STUDY 2: AIRFOIL ICING

MODELING THE EXTERNAL AIRFLOW AND WATER PARTICLES

Dispersed Multiphase model (DMP) → Mixture of **air** and **water droplets**

Air

One-way coupled



Water droplets

Unsteady airflow (Δt = 0.1s)

Ideal gas

Turbulent gas (K-Epsilon model)

Gravity

Droplet density: 10^3 kg/m^3

Droplet diameter: $2.1 \cdot 10^{-5}$ m

Droplet Volume Fraction: $3.42 \cdot 10^{-7}$

CASE STUDY 2: AIRFOIL ICING

MODELING THE IMPINGEMENT AND FORMATION OF FLUID FILM

Define the Phase Interactions:

Dispersed phase (DMP)

Continuous phase

→ Heat Transfer

Drag Force

Dispersed phase (DPM)

Fluid Film phase

→ Impingement

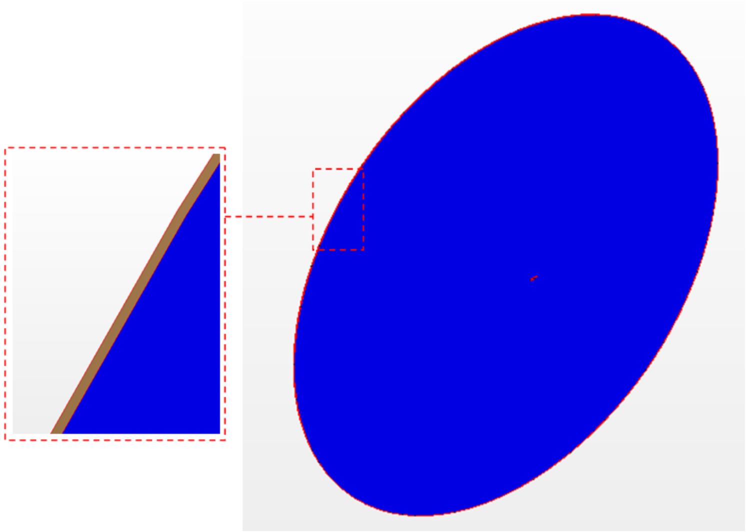
Define the Boundary Conditions

Inlet: Mach Number: 0.4

Static Temperature: 258.4 K

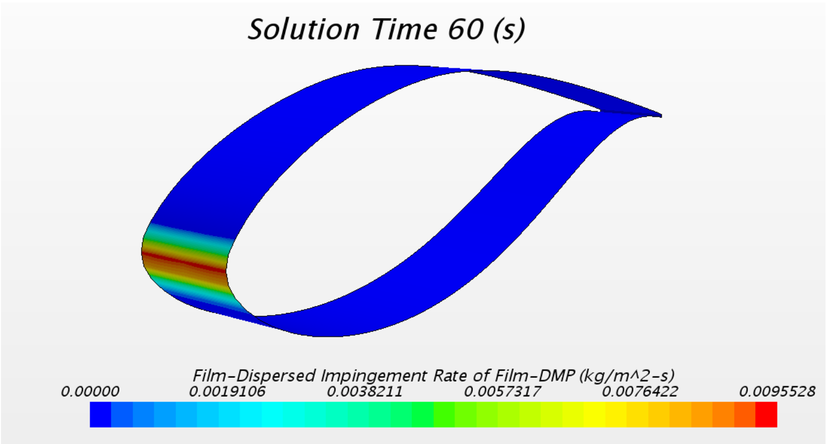
DPM Phase: Volume Fraction: $3.42 \cdot 10^{-7}$

Interface: Roughness Height: 0.1 mm



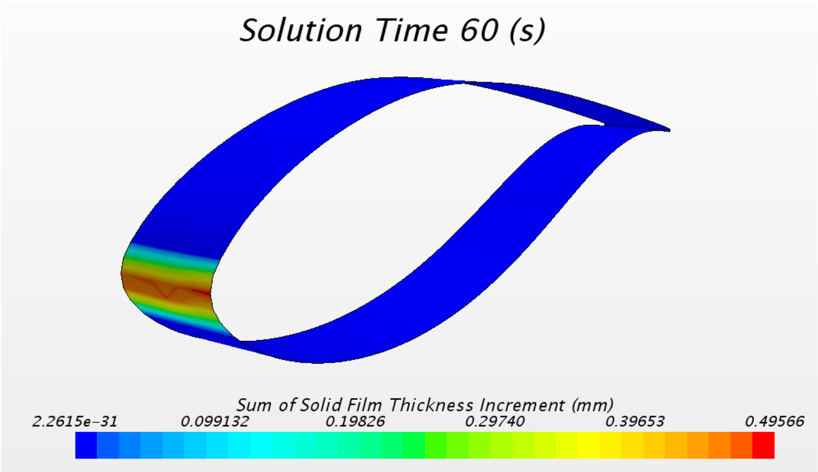
CASE STUDY 2: AIRFOIL ICING

MODELING THE IMPINGEMENT AND FORMATION OF FLUID FILM/ICE



Impingement Rate

Show the rate at which water droplet hit the surface of the airfoil



Solid Film Thickness Increment

Show the total amount of ice accumulated on the airfoil surface

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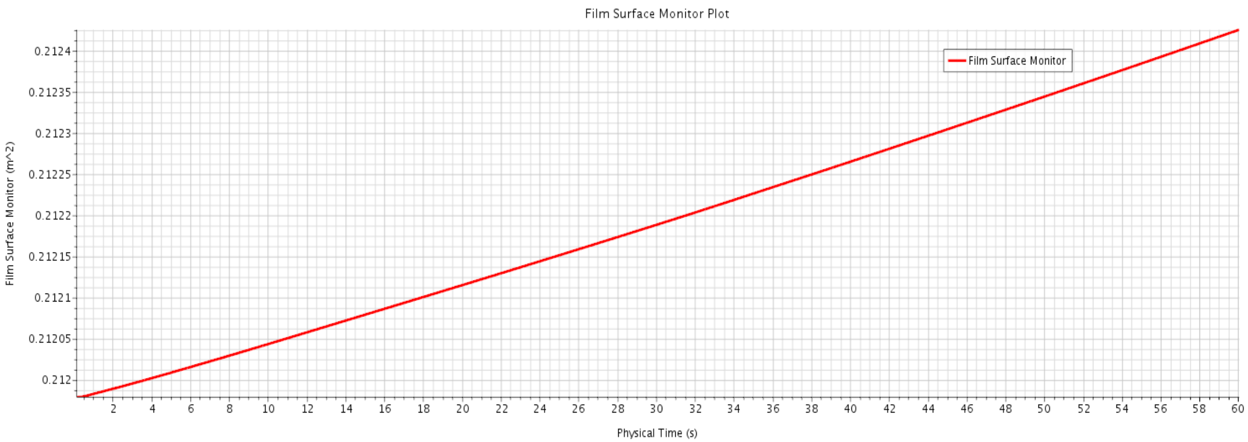
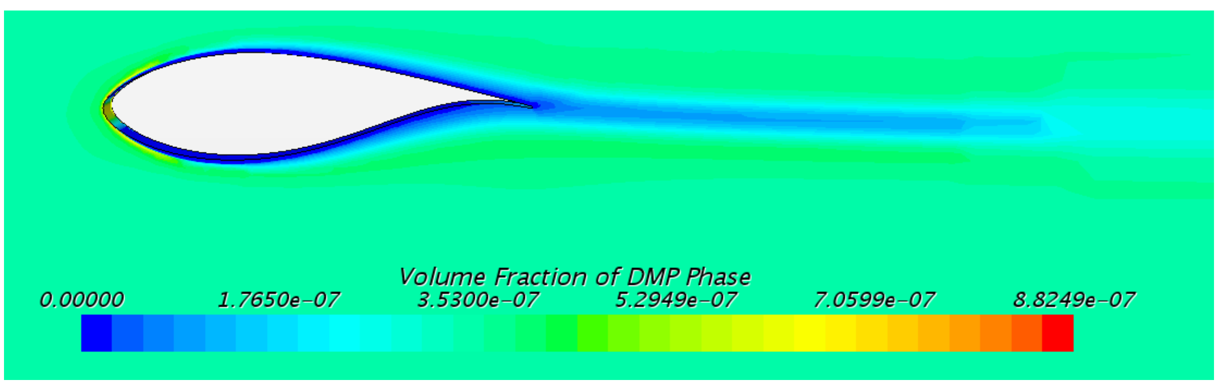


<u>Fluid Film Surface</u>

Monitor the quantity of film formed in the airfoil area



<u>DMP Volume Fraction</u>

The concentration of water droplets in air.

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İlginiz için teşekkür ederim!

Thank you for your attention!

Eskerrik asko zuen arretagatik!

¡Muchas gracias por vuestra atención!

eman ta zabal zazu
Universidad del País Vasco
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