IEA Wind Task 46
Erosion of wind turbine blades

Approaches for droplet impingement computation

Technical report

Alessio Castorrini
M. Sergio Campobasso

iea wind

Prepared for the
International Energy Agency Wind Implementing Agreement

Alessio Castorrini, Sapienza University of Rome, Italy and Lancaster University, UK
M. Sergio Campobasso, Lancaster University, UK

March 2025

Purpose

Leading edge erosion (LEE) of wind turbine blades has been identified as a major factor in decreased wind turbine blade lifetimes and energy output over time. Accordingly, the International Energy Agency Wind Technology Collaboration Programme (IEA Wind TCP) has created the Task 46 to undertake cooperative research in the key topic of blade erosion. Participatns in the task are given in Table 1.

The Task 46 under IEA Wind TCP is designed to improve understanding of the drivers of LEE, the geospatial and temporal variability in erosive events; the impact of LEE on the performance of wind plants and the cost/benefit of proposed mitigation strategies. Furthermore Task 46 seeks to increase the knowledge about erosion mechanics and the material properties at different scales, which drive the observable erosion resistance. Finally, the Task aims to identify the laboratory test setups which reproduce faithfully the failure modes observed in the field in the different protective solutions.

This report is a product of Work Package 3 Operation with erosion.

The objective of the work summarized in this report is to:

- Present high-fidelity state-of-the-art methods for calculating hydrometeor impingement characteristics in erosion analyses of wind turbine blades.

Table 1 IEA Wind Task 46 Participants.

Country	**Contracting Party**	**Active Organizations**
Belgium	The Federal Public Service of Economy, SMEs, Self-Employed and Energy	Engie
Canada	Natural Resources Canada	WEICan
Denmark	Danish Energy Agency	DTU (OA), Hempel, Ørsted A/S, PowerCurve, Siemens Gamesa Renewable Energy
Finland	Business Finland	VTT
Germany	Federal Ministry for Economic Affairs and Energy	Fraunhofer IWES, Covestro, Emil Frei (Freilacke), Nordex Energy SE, RWE, DNV, Mankiewicz, Henkel
Ireland	Sustainable Energy Authority of Ireland	South East Technology University, University of Galway, University of Limerick
Japan	New Energy and Industrial Technology Development Organization	AIST, Asahi Rubber Inc., Osaka University, Tokyo Gas Co.
Netherlands	Netherlands Enterprise Agency	TU Delft, TNO
Norway	Norwegian Water Resources and Energy Directorate	Equinor, University of Bergen, Statkraft
Spain	CIEMAT	CENER, Aerox, CEU Cardenal Herrera University, Nordex Energy Spain
United Kingdom	Offshore Renewable Energy Catapult	ORE Catapult, University of Bristol, Lancaster University, Imperial College London, Ilosta, Vestas
United States	U. S. Department of Energy	Cornell University, Sandia National Laboratories, 3M

Table of Contents

Figures

Executive Summary

The report summarizes high-fidelity computational approaches for determining the characteristics of the rain droplet impacts on wind turbine blades, an information paramount to blade leading edge erosion assessments. The methods, developed at Sapienza University of Rome, have been widely used for wind turbine erosion analysis, recently also in joint research programmes with Lancaster University. All methods summarized herein consider the blade geometry, the turbine controls and the site-specific wind and rain characteristics in the discussed multi-disciplinary erosion analysis framework. The methods can also account for the effect of the nonuniform aerodynamic field past the blades on the trajectories of the impinging rain droplet. Consideration of this physical aspect in the leading edge erosion analysis has been shown to result in an increase of about 10 percent on the leading edge coating durability with respect to the case in which the effect of blade aerodynamics on the droplet trajectories is ignored. More importantly, however, the more realistic erosion analyses that consider the aforementioned aerodynamic effects leads to a more accurate prediction of leading edge erosion topographies, which are paramount to accurately determine the blade performance loss and the associated turbine power and energy reductions due to leading edge erosion.

1. Introduction

Recent advances in the computational methods for predicting rain erosion of the blade leading edge (LE) aim to combine and improve erosion models, such as those derived by Springer [Springer et al. (1974), DNV (2020)], and the Palmgren-Miner rule to develop reliable methods for evaluating the damage level of protective LE coatings for site-specific rain and wind conditions. According to [DNV (2020), Eisenberg et al. (2018)], the damage accumulated by the blade's LE coating can be determined by using the Miner-Palmgren damage accumulation method, expressed by:

$$D = \sum_{i=1}^{N_d} \sum_{j=1}^{N_v} \left(\frac{n_{s,ij}}{N_{s,ij}} \right). \tag{1}$$

Indices *i* and *j* refer, respectively, to specific values of droplet diameter *d* and impact velocity *V*, whereas subscript *s* identifies a particular location on the surface, e.g., one of the small segments discretizing the airfoil profile of the blade strip being analyzed [Castorrini et al. (2024)]. $N_{s,ij}$ is the number of droplets per unit surface impacting segment s that would result in D=1, whereas $n_{s,ij}$ is the actual number of droplets per unit surface impacting the area.

In general, the value of $N_{s,ij}$ depends on the material properties of the coating and the underlying composite material (substrate), the erosion model, and the characteristics of the impacting droplets, i.e. droplet size *d* and component of the impact velocity normal to the considered area, given, in turn, by the product of the impact velocity *V* and the cosine of the impact angle θ). In general, the value of $n_{s,ij}$ depends on the site-specific distribution of wind speeds and droplet diameters, the turbulence of the wind, the wind turbine characteristics, e.g. blade length and wind turbine control characteristics, the geometry of the blade airfoils and the aerodynamic forces acting on the droplets approaching the blade. In general, one has:

$$n_{s,ij} = \mathrm{n_R}(\mathrm{i,j}) \frac{|\boldsymbol{V_b}|}{V_r} n_p(s) \tag{2}$$

where $\mathrm{n_R}(\mathrm{i,j})$ is the number of droplets per unit of ground surface with diameter di that falls in the reference period (typically one year) when the wind speed has value $V_{w,j}$, V_r is the droplet terminal velocity, $\boldsymbol{V_b}$ is the relative wind velocity vector at the blade surface and n_p is a s-dependent function expressing the fraction of the rain droplets upstream of the blade section ($n_R|\mathbf{V}_b|/Vr$) that actually hits segment s.

For the case in which the erosion analysis resolves the blade geometry, this report presents state-of-the-art approaches for computing function n_p, and also the impact velocity *V* of the impinging droplets and the angle θ between V and the normal to the impinged surface, developed by combining wind turbine engineering codes (e.g. NREL OpenFAST, DTU HAWC2, DNV Bladed, etc.), Computational Fluid Dynamics (CFD) and machine learning, when needed to improve computational efficiency. The integrated computational framework includes wind turbine controls and can account for wind turbulence. The two sections below provide details on how the framework works when the impact of blade aerodynamics on the impingement characteristics of the droplet is not considered (top plot of Fig. 1) and when it is (bottom plot of Fig. 1). In the latter case, the framework uses CFD to couple steady or unsteady aerodynamic simulations with Lagrangian particle tracking, enabling to simulate the droplet impingement considering the effect of the aerodynamic drag on the droplet trajectory.

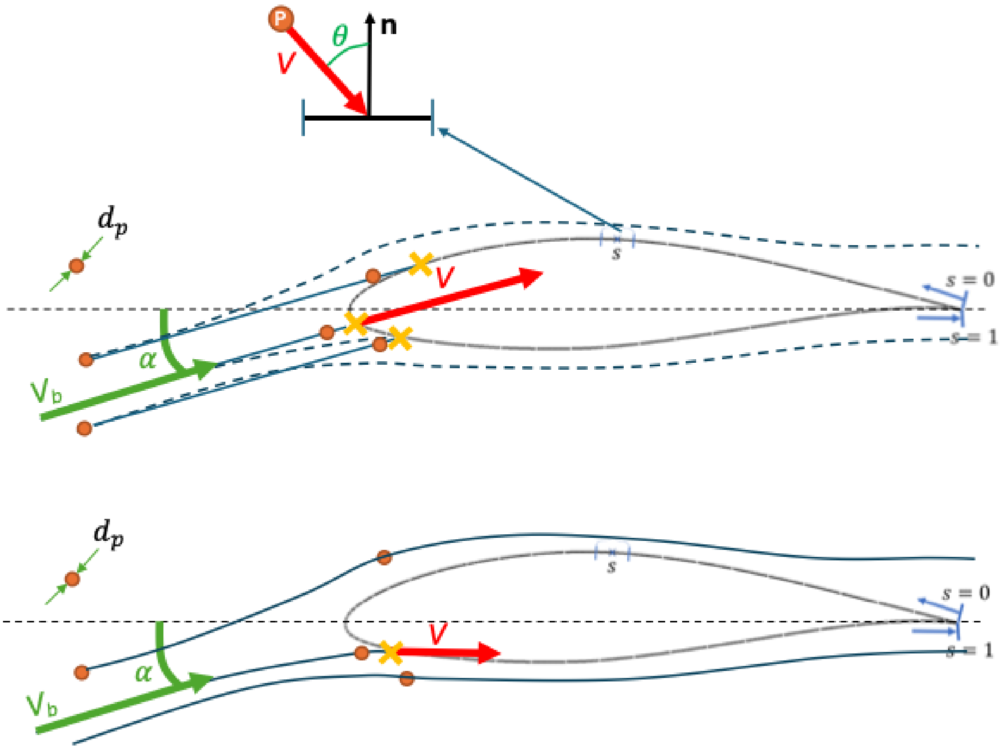

Figure 1. Particle trajectories and impact parameters. Geometrical projection approach (top), computing aerodynamic drag effect (down)

Guidance are also provided on incorporating in a computationally efficient manner the aerodynamic interactions of rain droplets and aerodynamic forces into leading edge erosion analyses by using machine learning-based metamodels. These metamodels enable to resolve droplet/aerodynamics interactions over comprehensive sets of wind turbine operating conditions at affordable computational costs.

2. Erosion analysis without droplet/aerodynamics interactions

Previous studies indicate that the rain droplets approaching wind turbine blades whose trajectories are most affected by aerodynamic forces are those with d<500 μm [Castorrini et al. (2021)]. Therefore, aerodynamic effects are expected to be most significant only for relatively small droplet sizes.

If one assumes that aerodynamic effects can be neglected in the computation of droplet trajectories, a simple geometric method can be applied to evaluate the impact characteristics (n_p, θ, V) at different locations along the 2D profile of a blade section at given radius. The geometric method assumes that all the droplet trajectories are parallel and the droplets move with the relative wind velocity at the blade section ($\boldsymbol{V_b}$) [Castorrini et al. (2024)]; then, the impact velocity is *V(s)* = $|\boldsymbol{V_b}|$, and the impact angle is:

$$\theta(s) = arccos\left(\frac{\boldsymbol{V_b}}{|\boldsymbol{V_b}|} \cdot \boldsymbol{n}(s)\right) \tag{3}$$

where $\mathbf{n}(s)$ is the normal unit vector of airfoil segment s of the blade strip under consideration. These values of *V(s)* and $\theta(s)$ are then used to determine the value of $N_{s,ij}$ in Eq. (1).

With reference to Eq. (2), in the present analysis which ignores the effect of aerodynamic forces on the droplet trajectories, one has:

$$n_p(s) = cos\big(\theta(s)\big). \tag{4}$$

3. Erosion analysis with droplet/aerodynamics interactions

The model described in the previous section does not account for blade aerodynamics in the calculation of the impingement pattern. As highlighted in Castorrini et al. (2024), including or neglecting aerodynamic effects on impingement may result in a 10% difference in the estimate of the coating lifetime for a wind turbine operating in a rainy environment typical of the UK. Consideration of the aerodynamic forces acting on the impinging droplets is particularly important when using models for the eroded mass loss, like that of the Springer model. This is because the modification of the impinging droplet trajectories due to consideration of blade aerodynamics alters the topology of the leading edge erosion patches. The assessment of the aerodynamic performance degradation is very sensitive to the erosion topography; thus, lack of aerodynamic modelling in the droplet impingement can reduce the accuracy of the aerodynamic analysis, and, ultimately, the estimate of the turbine power and energy losses.

The dynamics of droplet impingement can be resolved using a Lagrangian particle tracking (PT) approach. For levels of wind speeds and droplet concentrations contributing to rain erosion of wind turbine blades, the volume fraction of the dispersed phase lies below 10^{-6}. At volume fractions of 10^{-6} and lower, a one-way coupling approach is adequate for PT [Lain et al. (2003)]. The one-way coupling assumes that the particles do not influence significantly the aerodynamic field, but their trajectories are affected by the aerodynamic forces acting on them; these conditions allow the aerodynamic flow field to be computed with a solely aerodynamic CFD analysis only once, for each given far field condition. Then, this flow field can be used for several PT simulations, each considering a different droplet size.

The CFD framework is selected to derive a reliable solution for the velocity and turbulence field around the blade. When accounting also for the turbulent nature of wind, the dimensionality of the space of aerodynamic conditions to be considered for the erosion analyses is very large, also due to the wide range of wind turbine operating conditions. The presented approach aims to maintain a reasonably low computational cost by using 2D computations of blade sectional aerodynamics based on steady-state Reynolds-Averaged Navier–Stokes (RANS) CFD. It is noted that time-dependent and/or 3D CFD simulations can be easily integrated in this framework to possibly improve the overall accuracy of the erosion assessment.

In the studies carried out so far, the aerodynamic simulations are conducted using turbulence closure models that compute the mean turbulent kinetic energy field (e.g. k-ε or k-ω models) and capture the key aerodynamic characteristics of the high-Reynolds number flow past the blade sections. The boundary layer is generally resolved down to the wall (i.e. without using wall functions) to improve the accuracy of the computed velocity and pressure fields. However, this high level of grid refinement at the wall is not essential for the PT analysis, which at present uses the same grid of the aerodynamic analysis. This paves the way to further reductions of the computational cost of the PT assessment accomplished by using a coarser grid with aerodynamic field interpolated from the original CFD analysis. The cost reduction is expected to be particularly significant in the case of 3D CFD and PT analyses.

Once the steady or time-dependent aerodynamic flow field is computed, a concentration of discrete droplets can be injected into it; the injected particles can be tracked as material points whose velocity and acceleration are determined by solving the equation of dynamic equilibrium of the particles (ordinary differential equation) subjected to the aerodynamic drag resulting from the aerodynamic field in which they move. The drag depends on the size of the droplet, assumed to be spherical, which is an input parameter of the PT simulation. The weight of the particle is presently not considered. The extension can be made and requires the use of unsteady 3D simulations. It is yet unknown how much this addition would alter the impingement results of the present framework, since typical rain droplet sizes have mass corresponding to gravity force significantly smaller than aerodynamic forces.

Two approaches can be used to compute the trajectory of clouds of particles of given size, and determine the value of $n_p(s)$ in Eq. (2) and the values of $V(s)$ and $\theta(s)$ required to determine the value of $N_{s,ij}$ in Eq. (1). In both cases, an arbitrary but sufficiently large concentration of oncoming particles is prescribed in the computational domain, ahead of the blade section. These two methods are summarized in the following two subsections.

3.1 Method 1: single particle tracking

Each particle trajectory is computed by solving the simplified Basset–Boussinesq–Oseen (BBO) equations. The trajectory of each droplet is determined by balancing the inertial force, the aerodynamic drag, and modeling stochastic turbulent dispersion.
For cases in which the background flow field is computed with RANS CFD, the effects of turbulence on the particle trajectory are modeled via the discrete random walk (DRW) approach [Greifzu et al. (1997)], which introduces a fluctuating velocity component derived from the local turbulent kinetic energy. When a time-dependent simulation of the background aerodynamic flow field is used, the instantaneous velocity field is used directly for particle trajectory integration.

By employing a sufficiently dense seeding of particles along the injection region, the PT simulation captures statistical distributions of droplet impact parameters, i.e. the impact velocity *V(s)* and angle $\theta(s)$, and the impact density at the airfoil surface $n_p(s)$.

A schematic view of how method 1 works is reported in the top sketch of Fig. 2, whereas a sample results on the application of the method is provided in Fig. 3. The background aerodynamic flow field is reported on the left, and the computed droplet trajectories are reported on the right. The example refers to the airfoil at 70 percent blade length of a 5 MW turbine.

3.2 Method 2: aggregated Particle Tracking

This approach can be implemented according to two alternative methods, namely the “particle parcel method” [Patankar et al. 2001] and the “particle cloud method” [Castorrini et al. 2020].

- Particle Parcel Method: this approach assumes that a single material point represents a given number of particles. The material point acts as a sample particle, whose trajectory is assumed to be representative of multiple particles with the same motion. However, to achieve sufficient statistical accuracy, a large number of parcels must be injected into the simulation.
- Particle Cloud Method: this approach provides a statistical description of a cloud of particles distributed around its center of gravity (CG). The distribution around the CG is modeled as a probability density function (PDF), with characteristics related to the turbulence variables of the flow field. This method allows a smaller number of clouds to describe a large concentration field of particles while directly accounting for turbulence effects in terms of dispersion. As a result, the use of a random walk model becomes unnecessary. The equations governing the CG trajectories are a modified version of the BBO equations, incorporating ensemble averages. Further details of the method are available in [Castorrini et al. 2020].

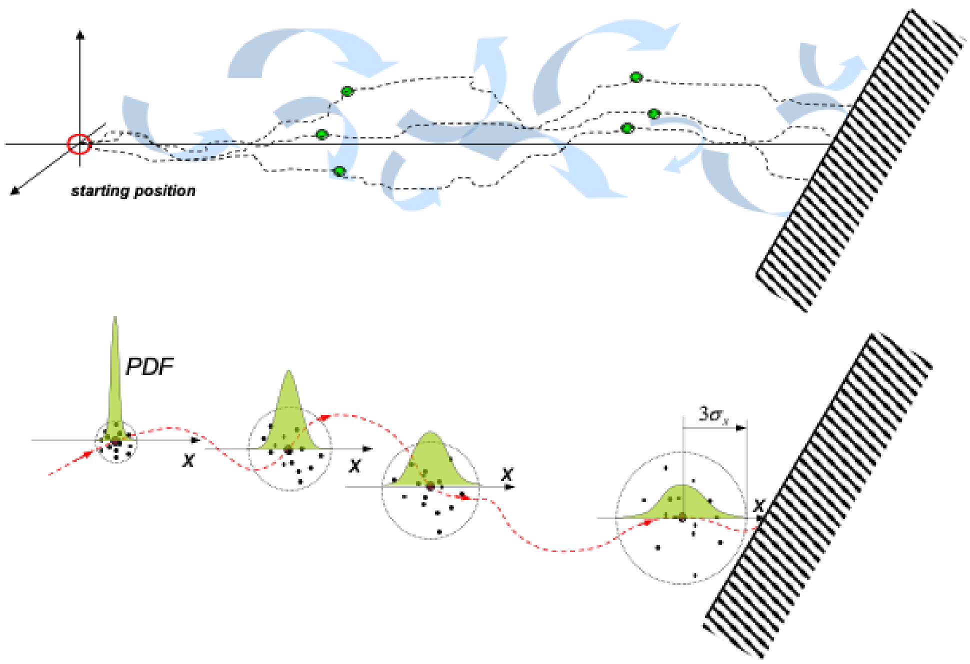

Figure 2. Single particle tracking (top) and cloud particle tracking (bottom) methods.

Once the trajectories have been determined, the impingement characteristics of each impacting particle is automatically defined. From this information one can define a model to derive the variable n_p. *V* and θ. In the PT simulations, the outputs of interest are collected at each airfoil segment *s* as follows:

- The impact density (i.e. number of impacting droplets per m^2 of wetted segment) is obtained by counting the number of impacting droplets in the simulation time and dividing the total number by the surface of the segment s. Then, $n_p(s)$ is obtained by dividing this result by the total number of injected particles per unit area of inflow surface [Castorrini et al. 2021].
- The impact velocity V(s) and impact angle θ(s) are time-averaged in the PT simulation.

A schematic view of how method 2 works is reported in the bottom sketch of Fig. 2.

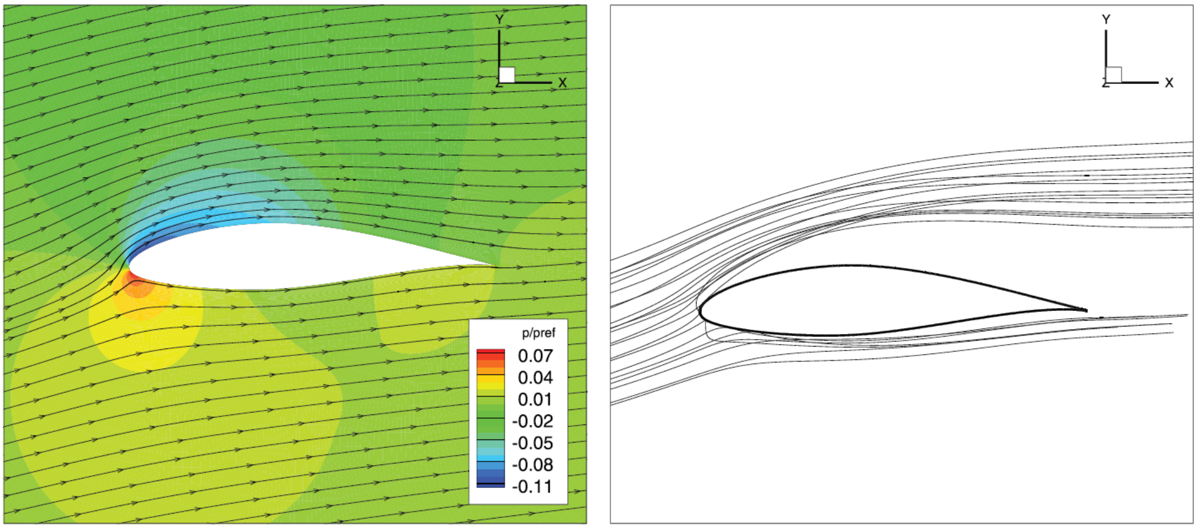

Figure 3. Flow field (left) and sample particle trajectories (right) for a 5MW blade section at 0.7R, Reynolds number 2.5 M and droplet size of 100 microns [Castorrini et al. (2021)].

4. Machine learning-based surrogate models for calculating impact characteristics

To reduce computational costs and enable rapid predictions across a wide range of operating conditions, surrogate modeling can be defined to interpolate between high-fidelity simulation results. A machine learning regressor can be trained on a large database generated from CFD and PT simulations. Following the approach proposed in [Castorrini et al. (2021)], a training dataset includes the 2D aerodynamic flow field obtained with a broad spectrum of far field conditions (Reynolds number and angle of attack) and the output parameters ($n_p(s)$, *V(s)*, θ*(s)*) of PT simulations obtained for each of these aerodynamic states by using different droplet sizes. By using these data to train a machine learning metamodel, a regressor can be obtained that returns the impact characteristics ($n_p(s)$, *V(s)*, θ*(s)*) for user-given values of droplet diameter, sectional Reynolds number, angle of attack without performing any CFD or PT analysis.

Figure 4 demonstrates that the surrogate defined for the test case in [Castorrini et al. (2021)] can achieve high predictive accuracy. This highlights the effectiveness of this regression tool, that provides near-instantaneous estimates of the impact characteristics.

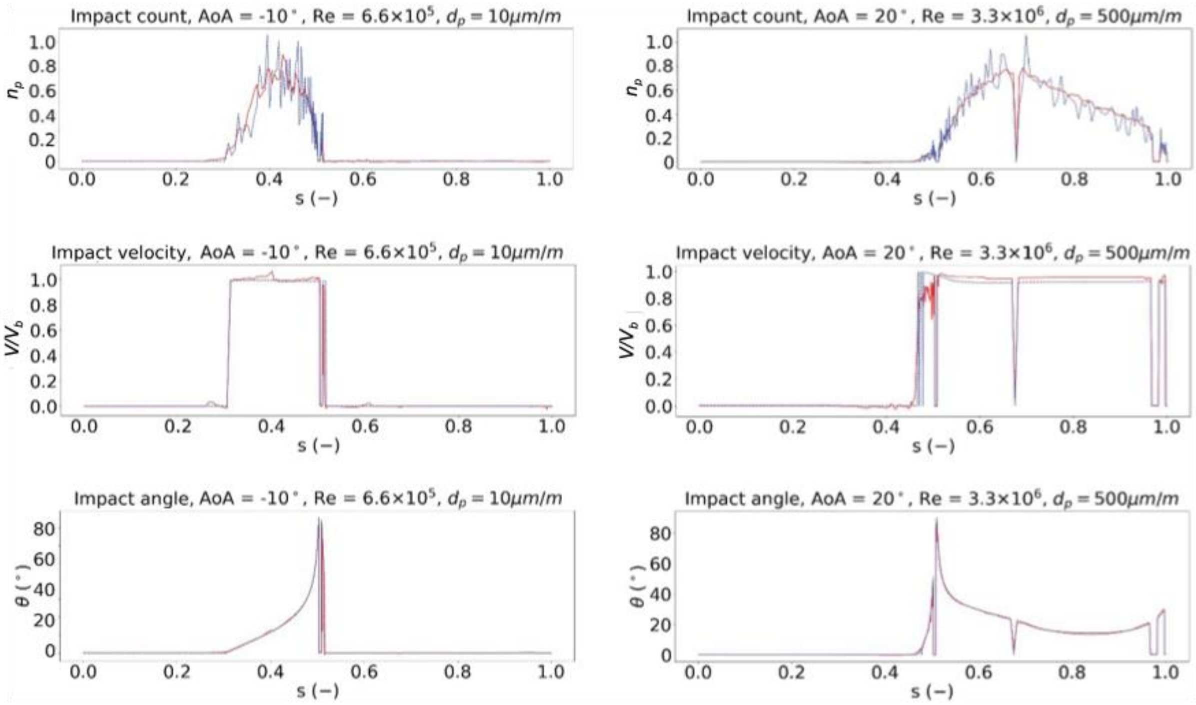

Figure 4. Impact pattern variables on the surface of NACA64-618 airfoil section for different angles of attack, Reynolds numbers, and droplet diameters. Blue: simulation, Red: surrogate model. (Source [Castorrini et al. (2021)])

References

Springer, G. S., Yang, C.-I., & Larsen, P. S. (1974). Analysis of rain erosion of coated materials. *Journal of Composite Materials, 8*(3), 229–252.

DNV. (2020). Evaluation of erosion and delamination for leading edge protection systems of rotor blades. *DNV-RP-0573.*

Eisenberg, D., Laustsen, S., & Stege, J. (2018). Wind turbine blade coating leading edge rain erosion model: Development and validation. *Wind Energy, 21*(10), 942–951.

Castorrini, A., Barnabei, V. F., Domenech, L., Šakalyté, A., Sánchez, F., & Campobasso, M. S. (2024). Impact of meteorological data factors and material characterization method on the predictions of leading edge erosion of wind turbine blades. *Renewable Energy, 227*, 120549.

Castorrini, A., Venturini, P., Corsini, A., & Rispoli, F. (2021). Machine learnt prediction method for rain erosion damage on wind turbine blades. *Wind Energy, 24*(8), 917–934.

Castorrini, A., Venturini, P., Corsini, A., Rispoli, F., Takizawa, K., & Tezduyar, T. E. (2020). Computational analysis of particle-laden-airflow erosion and experimental verification. *Computational Mechanics, 65*, 1549–1565.

Lain, S., & Sommerfeld, M. (2003). Turbulence modulation in dispersed two-phase flow laden with solids from a Lagrangian perspective. *International Journal of Heat and Fluid Flow, 24*, 616–625.

Greifzu, F., Kratzsch, C., Forgber, T., Lindner, F., & Schwarze, R. (1997). Assessment of particle-tracking models for dispersed particle-laden flows implemented in OpenFOAM and ANSYS FLUENT. *Engineering Applications of Computational Fluid Mechanics, 10*(1), 30–43.

Patankar, N. A., & Joseph, D. D. (2001). Modeling and numerical simulation of particulate flows by the Eulerian–Lagrangian approach. *International Journal of Multiphase Flow, 27*(10), 1659–1684.