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DOI

[10.1002/we.2272](https://doi.org/10.1002/we.2272)

Publication date

2018

Document Version

Final published version

Published in

Wind Energy

Citation (APA)

Bartolomé, L., & Teuwen, J. (2018). Prospective challenges in the experimentation of the rain erosion on the leading edge of wind turbine blades. *Wind Energy*. Advance online publication. <https://doi.org/10.1002/we.2272>

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REVIEW ARTICLE

Prospective challenges in the experimentation of the rain erosion on the leading edge of wind turbine blades

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Funding information

ADEM, A green Deal in Energy Materials of the Ministry of Economic Affairs of The Netherlands

Abstract

Developments in the wind industry reveal intricate engineering challenges, one of them being the erosion on the leading edge of the wind turbine blades. In this review work, the main issues for the wind industry in the experimentation with respect to erosion are examined. After a historical and general overview of erosion, this review focuses on the rain erosion on the leading edge of the wind turbine blades giving prominence to (1) the rain simulations, (2) experimental erosion facilities, and (3) variables to characterise erosion. These three factors have to be improved to establish a research field enabling the prediction of erosion behaviour and providing useful information about how the rainfall affects the leading edge of the wind turbine blades. Moreover, these improvements in the experimentation of the erosion would be a first step to understand and predict the erosion damage of the wind turbine blades. Finally, this review work also will help to cope with experimental investigations and results in the rain erosion on the leading edge with a deeper critical thinking for future researchers.

KEYWORDS

erosion, erosion tester, leading edge, rain simulation, wind energy

1 | INTRODUCTION

Wind has become one of the most promising sustainable energy sources due to the low to null pollution emissions when the kinetic energy from the wind is converted into electrical power in the wind turbines. Therefore, the research and innovation in the wind energy industry have led to a rapid increase in the wind power capacity during the last two decades. In the year 2000, the total wind power capacity was 12.9 GW in the European Union (EU), whereas it was 154 GW in 2016, with 12.5 GW installed power in this year alone.¹ Furthermore, a rise up to installed capacity of 320 GW has been estimated before 2030 in the EU.² Not only in Europe, also in the United States (US), nowadays there is 82 GW of installed wind power capacity that supplies 6.4% of the electrical demand.³ The US Department of Energy has targeted that wind power will supply 20% of the electrical demand in 2030.⁴ Moreover, China currently is the largest market for the wind energy industry with a total installed wind power capacity of 168 GW at the end of 2016. Furthermore other countries, as India, Canada, and Brazil, are rapidly entering this market with growths in installed power of 55% (from 18.4 to 28.7 GW), 92% (from 6.2 to 11.9 GW), and 330% (from 2.5 to 10.75 GW), respectively, since 2012 until 2016.⁵ To cover the requirements of this market growth, the scale of the wind turbines, especially the diameter of the blade rotor, has greatly increased during last years (Figure 1). In this way, for example, the current average onshore turbine capacity becomes of the order of 3 MW, whereas it was below 1 MW in the 1990s.⁷ However, this augmentation in diameter also entails an increase in the speed of the tip of the blades, and therefore, at the same time, the operation and maintenance (O&M) costs also have been dramatically increased.⁶ Thus, the cost reduction in O&M has become a challenge for the wind energy industry.

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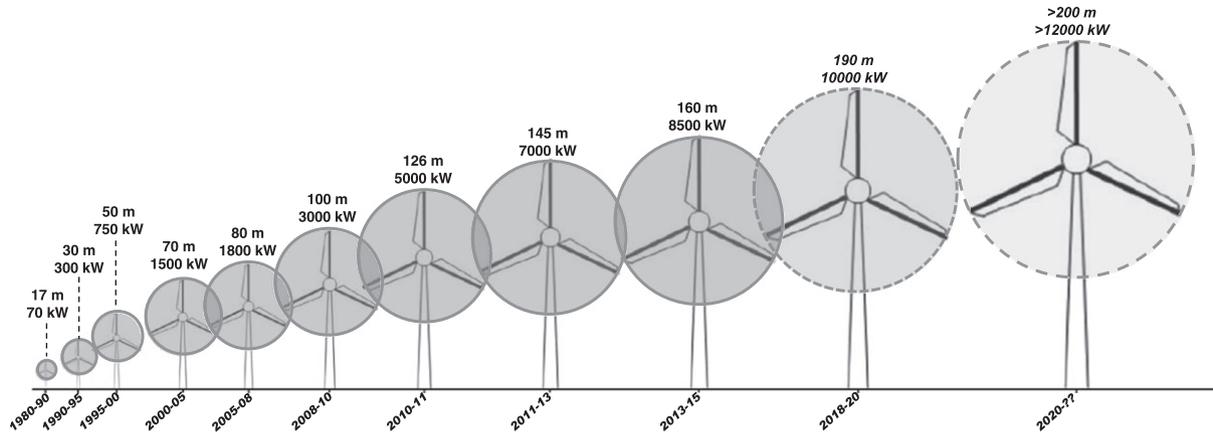


FIGURE 1 Growth in size and power of wind turbines during last years and prospects [adapted from IEA Report⁶]

Of the O&M costs, the reduction of costs due to damage and failure represents an interesting engineering challenge for the wind energy industry due to the coverage of different research issues in engineering, eg, material science, structural integrity, manufacturing processes, and tribology. The damage should be understood as changes to the constitutive material and/or the geometric properties, including alterations to the boundary conditions and structural connectivity, which can adversely affect structural and power performance.⁸ Thus, several issues have been studied, eg, manufacturing process,^{9,10} fracture,¹¹ fatigue,¹² and adhesive joints.¹³ Although diverse turbine designs exist, currently the most common design is built in an upwind horizontal axis with three blades. Considering this common design, the damages, also classified as failures, range from cracks, debonding, lightning damage to corrosion, erosion, or leakages, and they occur in all the parts of the wind turbine, eg, drive train, tower, nacelle, blades, or control system. From all the damages in wind turbines, the blade damage or failure is the most frequently reported.¹⁴

Nowadays, the wind turbine blades are manufactured to obtain an optimum performance, ie, they are designed to develop an optimum lift to sustain their rotational motion, based on a balance between structural integrity and weight.¹⁵ Thereby, the polymer composite materials are principally utilised to produce the main blade components (Figure 2). The blades are fundamentally composed of two shells forming an airfoil shape from thermosetting polymer matrix, eg, epoxy or polyester, with reinforcing fibres.^{17,18} These two shells are bonded using adhesive and creating the leading and trailing edges. This airfoil-shaped blade is stiffened by spars or webs from balsa wood, foam, or combinations of both.^{19,20} Moreover, a root joint connects the blade to the rotor. All these blade components may suffer a variety of damages and failures (see Table 1) which can be observed in operating wind turbines.^{16,21,22} Therefore, for the wind industry, the study to understand how these blade failures or damages occur has become highly promising as well as challenging.

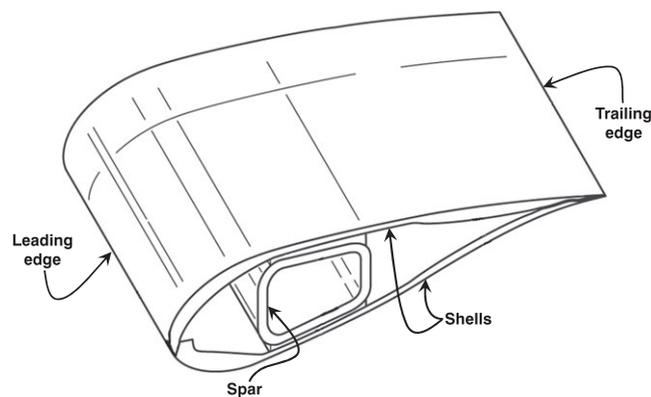


FIGURE 2 Main components of the wind turbine blades [modified from Sørensen et al¹⁶]

TABLE 1 Damages and failures typically observed in blade components during operation time

Blade Components	Damages and Failures
Root joint	Cracks, wrinkles
Shells	Splitting and transverse cracks, delamination, debonding
Spar	Cracks, wrinkles, sandwich and adhesive debondings, delamination
Leading edge	Erosion, adhesive debonding, splitting cracks
Trailing edge	Longitudinal and transverse cracks, adhesive debonding

The causes of the failures and damages in blades are mostly related to design, manufacturing, environmental effects, and ageing. Some of the failures and damages, eg, wrinkles, and debonding, are basically inherent to the design and manufacturing processes whereas other ones, eg, erosion and splitting cracks, are more related to environmental effects, wild life, and ageing.²³ The regions along the axial locations of 30% to 35% and 70% of blade length from the root joint are more prone to the failures and damages due to the design and manufacturing processes.¹⁴ However, the leading edge is more prone to the damage due to the environmental effects and wild life.

A variety of environmental effects, eg, hailstorms, snow, rain showers, wind gusts, icing, extreme temperatures, lightning, sea water, ultraviolet light, and sandy winds, degrade the blades of wind turbines over their working lifetimes. This degradation leads to reduction in aerodynamic efficiency and power production, eg, the degradation caused by erosion on the leading edge affects the drag and the lift. Depending on the drag increase and lift decrease, the loss of the annual energy production of wind turbines can range from 2% to 25%.²⁴ Therefore, the reduction of erosion is a meaningful engineering challenge even more so taking into account that a relatively small degree of leading edge erosion can cause a large increase in drag.

This review assesses the current developments in research of the leading edge erosion and also some of the issues and challenges that should be coped in the near future for establishing a more rigorous scientific framework which provides a better understanding of and solutions for erosion to the wind energy industry. Therefore, the next section describes the main aspects of the erosion and some of the historical problems that arise during the study of erosion. The third section focuses on the erosion on the leading edge and which are the main issues, in for instance rain simulations, erosion test facilities, and variables of erosion analysis, to be considered to improve the scientific rigour of the research in the rain erosion of the wind turbine blades. Finally, the main conclusions along with the approaches to some of these issues are recapitulated in the last section.

2 | EROSION

Erosion is defined as the progressive material loss from a solid surface due to repeated impacts of solid or fluid particles. Unlike wear, in erosion, there is a fluid contribution to the mechanical phenomenon that is producing the material loss.²⁵

Due to the complexity of the erosion, an erosion theory from first principles, ie, which relies on basic laws of nature without additional assumptions or empirical models, is strongly difficult to derive.²⁶ The complex phenomenon of material removal makes barely possible the direct establishing of a proper predictive theory. For similar reasons, general relationships between erosive removal and macroscopic mechanical properties are highly complicated to establish. Considering that a completely theoretical predictive model is unlikely to be oncoming, a semi-empirical model is a logical approach. Therefore, the access to quality experimental work which contributes to this semi-empirical approach becomes essential to comprehend the erosion. Consequently, throughout the years, the creation and improvement of experimental facilities have played a significant role in erosion research. Different purposes can be established in the erosion analyses. Frequently, the aim is simply to compare the relative erosive resistance of one material with other materials.^{27,28} But another aim can be to detect and define the damage mechanisms so the intrinsic erosive resistance of a material can be improved.^{29,30}

2.1 | Forms of erosion

Although the erosion is an effect that can be easily identified due to the surface damage, the erosion presents itself in different forms. The foremost forms are caused by solid particles, slurries, impingements, droplets, and cavitation.²⁵ All these forms are not presented on the leading edge, but briefly explaining them could help to provide an overall context and to understand the additional forms of erosion on the leading edge, eg, erosion due to sand or salt water. The solid particle erosion is the caused damage on the surface of a body by the successive impacts of solid particles which are driven within a gas.^{31,32} The solid particle erosion is relevant to, among others, comminution devices, mining, gas extraction, cyclone separators, and aircraft propellers. The slurry erosion is similar to the solid particle erosion, but the particles are driven within a liquid.^{33,34}

This erosion form is important in mining, extraction of petroleum, and piping. The impingement erosion is mainly caused when a liquid stream impacts on a solid surface causing fracture, which can be conjoint with corrosion. The impingement erosion is especially relevant in the chemistry industry when chemicals are transported in pipelines or introduced into vessels.^{35,36} The droplet erosion is also caused by liquid flow but composed of drops.^{37,38} In this case, the rain erosion is the main kind and therefore it is significant in outside industrial applications, eg, aircraft and wind turbine industries. Finally, the cavitation erosion is caused when entrained gas cavities or bubbles within a liquid collapse.²⁵ Cavitation erosion occurs in many industrial applications, eg, concrete spillway, hydroelectric dams, when a liquid flows in piping and pumps³⁹ and jewellery industry for cleaning purposes.⁴⁰

2.2 | Historical industrial relevance of erosion

The study of erosion as a damage concern goes back to the early 20th century when materials with high erosion resistance were sought to be used in steam turbine blades.^{41,42} The blades of steam turbines rotate at supersonic velocities within wet steam environments suffering water droplet impacts and hence erosion. These early studies were trying to relate erosion performance to mechanical properties of different materials. However, even if the lack of accurate experimental facilities is not considered, the achieved success was reduced due to the complexity of erosion as a mechanical process.⁴³ During the 1940s, erosion was also detected as a severe damage phenomenon by the aeronautical industry.^{44,45} The erosion was particularly intense on the forward facing components of aircrafts, eg, leading edges and radomes.⁴⁶ Actually, the aircraft industry has developed metallic shields and polymeric coatings or tapes to mitigate the erosion on the exposed parts. These solutions are developed for the

aircraft industry where inspections of the wing leading edge can be carried out when the airplane is on the ground, but they can be unfit for other industries, eg, in wind industry where inspections are more spaced out over time due to limited accessibility and to reduce the O&M costs.

During the last decades, a wide range of disciplines and industries have also been greatly interested in erosion as wear phenomenon, eg, high-speed cutting materials, chemical plants, mining surface cleaning, or medical sciences. The erosion is very widespread and is involved in a considerable number of processes. The extraction of minerals and oil produces erosion on the drilling tools.^{47,48} The sand-, dirt-, dust-laden air causes erosion on the propellers, impellers, and fan drives.^{49,50} The cutting tools in high speed manufacturing are also affected by erosion.^{51,52} The rain-drop impacts erode the exposed surfaces of the aircrafts, eg, leading edge of wings.⁵³ In farming, the tillage tools are eroded by soil and rocks.^{54,55} In dentistry, the erosion is used for teeth cleaning, but also some of the dentist instruments induce erosion on the teeth to prepare them for dental treatments.⁵⁶ Consequently, due to the large quantity of erosive applications that can be found in different industrial fields, the erosion has a great economic impact. Currently, due to the effect in the energy production and therefore in the economic profit, the research in erosion, specifically in rain erosion, has become a problem subjected to a broad undergoing interest due to the development in wind turbine industry during the last decades.

3 | RAIN EROSION IN BLADE LEADING EDGE

This section focuses on the rain erosion on the leading edge of the wind turbine blades and how its experimental research should cope with several challenges to characterise the erosion caused by the raindrops with proper scientific rigour.

Erosion occurs on the leading edge of wind turbine blades that have been in operation because of various environmental conditions. Atmospheric particles, raindrops, hail,³⁷ and sand⁵⁷ impacting the wind turbine blades rotating at high speeds is the primary cause of surface erosion on the leading edges. These impacts start modifying the surface roughness, then changing the shape, ie, the aerodynamic profile, of the leading edge and in the end damaging the integrity of the blade material. Wind speed and rotational velocity of the blade determine the impact velocity of the erosive particles and hence the erosion capacity, ie, the power to cause erosion. Although the tip of the blade is the most prone part to suffer erosion due to the maximum rotational velocity is at this part, erosion can be also found in parts closer to the hub along the leading edge. Moreover, the extent of erosion also depends on the environmental temperature and humidity.⁵⁸

Among all the causes of erosion on the leading edge of the wind turbine blades, rain is one of the most important because it causes erosion since the first moment the wind turbines start working, eg, Wood⁵⁹ found that, although the blades are expected to run more than 20 years, erosion can occur after only 2 years of operation. Initially, the raindrops cause change only in superficial roughness, ie, no visual effects can be found and gravimetrically no significant changes can be measured. This time is usually referred to as incubation period.⁶⁰ To the wind industry, this period will be of great importance as its enlargement will prolong the time of full power capacity of the wind turbines. During this period, the microstructural characteristics of the material at the leading edge yield nucleation points for the initiation of the material removal.⁶¹ Therefore, after the incubation period, the erosion begins to be visible and the loss of mass can be measured. The first observable effects on the surface of the leading edge are irregularly distributed pitting (Figure 3A), then the increasing density of pitting makes surface pits combine and thus cracks can be formed easily starting the cracking (Figure 3B). After that, severe erosion begins when cratering (Figure 3C) appears due to the high concentration of cracks at some points. Finally, the cluster of cracks becomes a failure of the material integrity, ie, the complete removal of the coating layer exposes the laminates and thus delamination (Figure 3D) occurs. All these stages of erosion do not have to strictly occur in this order because factors, eg, manufacturing, transport, and installation, also may induce small tears or scratches which play a role as initiation points of erosion altering the natural process of erosion on the leading edge of wind turbine blades.⁶²

Although the study of the rain erosion on the leading edge has become an essential issue for the wind turbine industry to reduce maintenance costs and to increase the annual energy production, the available literature about the cause and the mechanisms of rain erosion is very limited. Mainly, the reasons for this scarce literature are that the sources, as manufacturers, operators, and maintenance and repair companies, rarely provide details about the issue of rain erosion on the leading edge and, when they provide them, the information is referred to the first-hand experiences with anecdotal reports.⁶³⁻⁶⁵ However, during the last years, the monitoring and recording of the erosion have been carried out to detect the correlations between the leading edge erosion and the climate and operating conditions by wind industry.⁶⁶ Although these databases will be able to provide useful and practical information for wind industry, some experimental challenges in the erosion of the leading edge need to be addressed from a scientific point of view to promote a research field which will be really productive and with the capacity of prediction for the wind industry. Some of these main experimental challenges are in rain simulation, experimental test facilities, and variables for rain erosion.

3.1 | Rain simulation

The erosion on the leading edge of the blades is caused mainly by rain. Therefore rain, and more specifically the amount of rain water, ie, the rain load, in each rainfall event, is interesting to experimental research, and many works can be found in the literature to handle rain data,^{67,68} but rain is a natural phenomenon which is strongly complex to simulate. This complexity is derived from several factors, the most important being size, shape, and velocity of the raindrops.⁶⁹

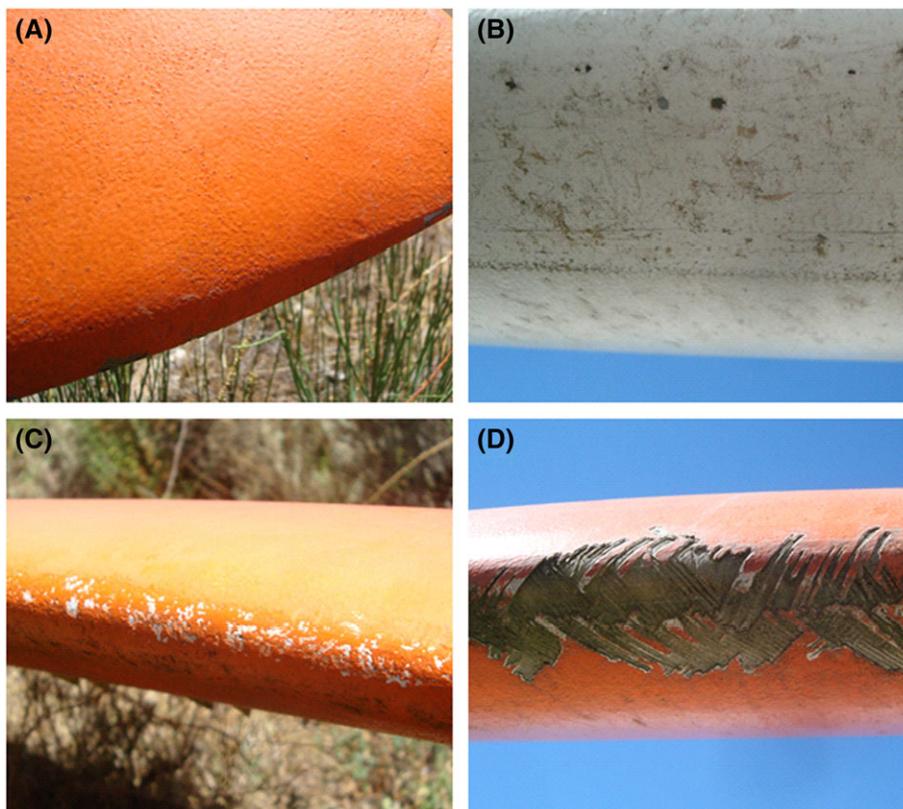


FIGURE 3 Progressive stages: A, pitting; B, cracking; C, cratering; and D, delamination, of the rain erosion on the leading edge of blades [Colour figure can be viewed at wileyonlinelibrary.com]

Firstly, the size of the drops during rainfall is not homogeneous and follows a continuous distribution which indicates the number of raindrops with a specific diameter in a unit volume of air.⁷⁰ Moreover, the intensity of the rainfall determines the prevalence of a certain diameter and hence the maximum diameter of the raindrops (Figure 4).

Secondly, the shape of the raindrops depends on the size; up to 2-mm diameter, the raindrops are almost spherical, between 2 and 5 mm, the shape is more semi-oblate, ie, flat on the down part, and bigger than 5 mm, the shape is close to parachute form (Figure 5), which becomes unstable and can fragment into smaller drops. The maximum diameter of a raindrop that has been found is around 10 mm in very specific cases but usually the raindrops fragment at smaller diameters.⁷¹ Moreover, falling raindrops are subject to coalescence, ie, two or more contacting raindrops merge to form a bigger new single raindrop. Therefore, the shape of the raindrops is highly dynamic, ie, changing constantly, during their drop down in rainfalls.

Thirdly, as the raindrops fall through the air, then the terminal velocity, ie, the highest velocity attainable by a body falling through a fluid, is the characteristic velocity close to the land. The terminal velocity of falling raindrops depends on the drop mass, the humidity, the temperature, and orography, ie, the topographic relief of mountains, and also is affected by wind. Therefore, although determining the actual terminal velocity of the drops in each rainfall is almost unattainable, there are some approximations to obtain theoretical results,⁷² in which the terminal velocity V_t of falling raindrops through static air is related to the stable raindrop diameters D_0 , the gravity g , and the density of the drop and the air ρ and ρ_a , respectively:

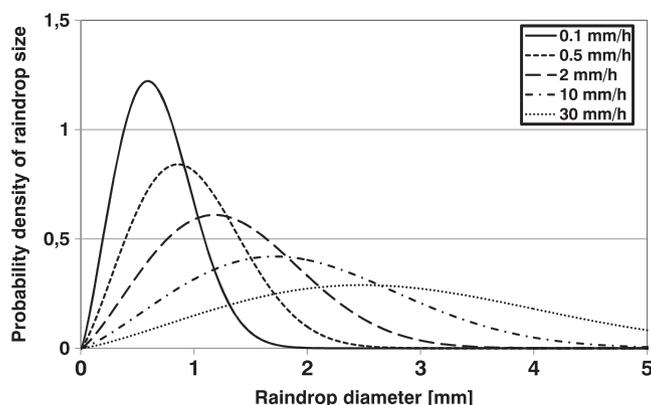


FIGURE 4 Probability density of the raindrop diameters depending on the rainfall intensity [using equation from Best⁷⁰]

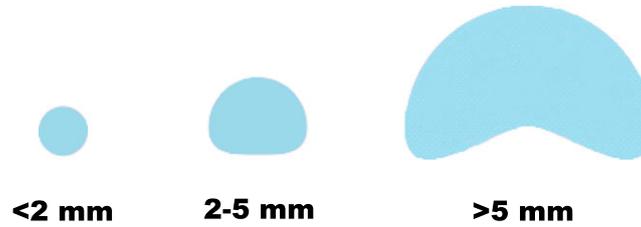


FIGURE 5 Shape of the raindrops depending on the diameter [adapted from Villermaux and Bossa⁷¹] [Colour figure can be viewed at wileyonlinelibrary.com]

$$V_t \cong \sqrt{(\rho/\rho_a)gD_0} \quad (1)$$

Apart from this complexity in simulating rain itself due to size, shape, and velocity of raindrops, the modelling of the rain as an erosive phenomenon is still lacking the proper solutions. The studies to find models of the rain as erosive phenomenon have been carried out mainly using traditionally two different approaches, ie, the approaches have been considering the impact force⁷² or the energy transmitted.⁷³

3.1.1 | Impact approach

The impact approach is historically based on the waterhammer equation:

$$P = \rho_l c_l v_i. \quad (2)$$

This equation predicts the impact pressure P on the surface body by a liquid drop with density ρ_l , being c_l the speed of sound in the liquid and v_i the impact velocity, assuming that (1) the impact occurs in one dimension, (2) a perfectly rigid body, and (3) speed of sound and density constant.⁷⁴ Despite these assumptions, the waterhammer equation determines the magnitude of the impact pressure in good approximation that can be used as an indication of the level of initial pressures during the impact which can be, for impact velocities of around 100 ms^{-1} , of the order of giga-pascals during fractions of a microsecond.⁷⁵

However, the analysis of the impact droplet on a solid surface is more complex. After the initial supersonic expansion of the contact area, the initial compressional wave evolves in shear, reflected, and Rayleigh waves which depend on the impact conditions and the mechanical properties of the rigid body.⁷⁵ In addition, a lateral outflow of liquid, named jetting, happens after the compress reflection front passes the edge of the initial contact area and creating a decompression that can reduce the initial pressures up to one order of magnitude.⁷⁴ Otherwise, Fu et al,⁷⁶ using the measured impact force of a single raindrop by a transducer, calculated the rain load based on the fitting formula of peak force and the normalized curve of raindrop impinging force.

Regarding the leading edge erosion, the impact force approach was followed by Slot et al⁷⁷ to establish an erosion model which can predict the life of the leading edge of coated wind turbine blades. Using the linear cumulative damage rule of Palmgren-Miner⁷⁸ and a modified waterhammer equation:

$$P = \frac{V \rho_l c_l \rho_s c_s}{\rho_l c_l + \rho_s c_s}. \quad (3)$$

Proposed by Dear and Field⁷⁹ where the subscripts l and s are referred to the liquid and the solid, respectively, the coating life is estimated as the incubation period. However, this theoretical model assumes the impacts of the raindrops being independent of each other, ie, without interaction between them. Moreover, this attempt tries to apply the roller bearing protocol where only the fatigue is the cause of damage, but other causes of damage are exhibited during rain erosion, eg, impact damage, abrasion.

Finally, due to the development of computational power during the last decades, the capacity to numerically model the liquid impact on a solid has been enhanced. The first efforts using finite elements were performed by Adler⁸⁰ for polymeric materials in aircraft studies. In regard to erosion leading edge, Keegan et al⁸¹ conducted a numerical model of the normal impact of a 3-mm diameter raindrop on an epoxy resin, as typical wind turbine blade composite, plate. However, this model did not consider multiple raindrop impacts, different impact angles, or residual stresses during blade manufacturing. Recently, Amirzadeh et al⁸² developed a computational framework for the analysis of rain erosion on wind turbine blades using a stochastic rain model to generate three-dimensional domains of raindrops. These generated domains intend to be consistent with the rainfall at specific locations integrating raindrop size and spatial distribution with rain intensity and average volume fraction of raindrops. However, as a stochastic phenomenon, the rain is considered perfectly random; thus, the raindrops are uniformly distributed in space without taking into account the rain dynamics, eg, coalescence. Moreover, for this framework, the impacts are only in the normal direction for only perfectly spherical raindrops with neglected terminal velocity.

3.1.2 | Energetic approach

The energetic approach is based on the kinetic energy transmitted, and this approach tries to relate erosion to mechanical properties of the impacted body. Nevertheless, the difficulty lies in quantifying the total transferred energy to the bulk of the body through the surface. Although this approach has been explored in other cases such as steam blade turbines,^{83,84} energetic-based studies regarding the erosion on the leading edge are lacking in the scientific literature. Therefore, studies on this approach are promising because it tries to analyse the erosive capacity of the rain as a whole avoiding the actual assumptions, eg, the impact effects are independent of each other, the shape of the raindrops as a perfect sphere, etc.

3.2 | Experimental test facilities

Throughout the years, many experimental test facilities and instruments have been developed to investigate erosion.²⁵ Nowadays, to study the rain erosion, principally two kinds of experimental facilities are employed: the jet erosion test facilities and the whirling arm test facilities, although other kinds of facilities can be found in the literature, as rocket sledge and single drop impact test.⁸⁵ The former facility basically consists of a nozzle ejecting water under high pressure over the sample (Figure 6). The jet can be continuous,^{86,87} unstably causing droplets,^{81,88} cut by a rotating body creating water jet slugs^{89,90} or the multiple impact jet apparatus where discrete water jets are created on the nozzle electromechanically.⁹¹ The whirling arm test facility consists of a horizontally rotating arm subjected to an artificially created rainfall. These two erosion test facilities present different advantages and disadvantages which are summed up in Table 2. Several authors^{89,90} have found that the obtained experimental results from these both erosion test facilities cannot be, at least directly, correlated, ie, the relative erosion resistance between a list of the same materials can be quite different depending on the used test facility. Although the reason of lack of correlation is not clear, how the water drops impact on the sample seems to be the main motive among others factors like the distribution in size of water drops, the presence of a buffer water film on the surface sample.

During the last 50 years, the aircraft industry has used the whirling arm test facilities to evaluate materials and investigate rain erosion, eg, the rain erosion test facility (Figure 7) of the Air Force Research Laboratory (AFRL) at the University of Dayton Research Institute (UDRI) has been conducted and involved in rain erosion research since 1964 with almost 150 000 evaluations.⁹² Although the whirling arm test facilities have produced a great amount of useful information about the erosion resistance of different materials that are utilized by the aerospace components. Regrettably, the comparison of the obtained results between different test facilities has always been difficult because the process has not been completely standardised and the used test conditions by each facility have been complex to replicate. Therefore, the whirling arm erosion test facilities have inherent characteristics which reduce confidence in the test results, eg, the aerodynamic behaviour of the water drops is uncertain when the arm starts rotating or the heating due to the friction of the rotating samples with the air. In addition, on the same whirling arm test facility, differences in results for the same material were also found when changes of the tests conditions are carried out.⁸⁹ Consequently, a serious discussion about the reasons for this scatter in test results is essential. Moreover, historically the diameter of the artificial water drops in most test facilities has been around 2 mm.⁵³ A target diameter allows, at least in theory, to compare the results between facilities, but this specific diameter corresponds to a rainfall of intensity around 20 mm h⁻¹ which is considered a heavy rain. Therefore, the experimental results of erosion are unsuitable if they want to predict the useful life of the tested components.

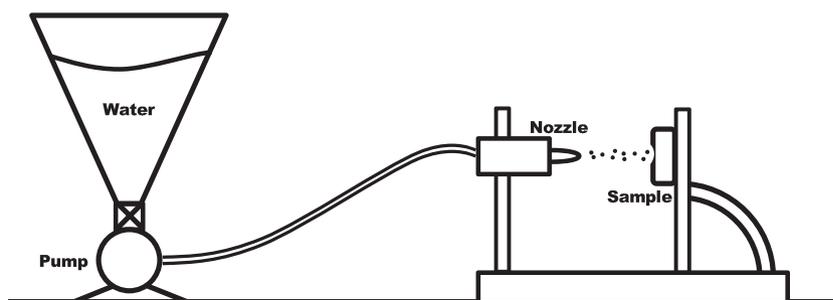


FIGURE 6 Schematic illustration of the jet erosion test facility

TABLE 2 Advantages and disadvantages of jet erosion testers and whirling-arm testers

Jet Erosion Test Facility		Whirling Arm Test Facility	
Advantages	Disadvantages	Advantages	Disadvantages
Cheap fabrication of facility	Small geometry of sample	Extended erosion area	Expensive fabrication of test set-up
Easy operation	Intensive erosion area	Reproducible results	Fixed geometry and mass of sample
Flexible shape of sample	Low reproducibility of results	Good for comparison of relative erosion resistance	Complex aerodynamic environment
			Poor interchangeability of results among testers

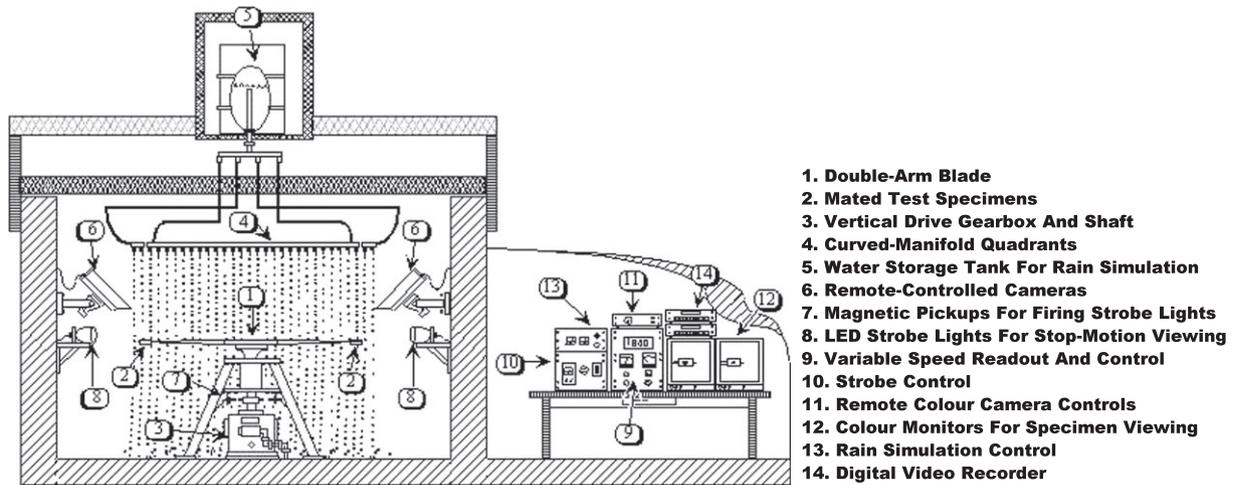


FIGURE 7 Schematic illustration of the AFRL rain erosion test facility⁹²

Regarding the erosion on the leading edge of the wind turbine blades, the erosion resistance of the leading edge protection systems has been evaluated mainly using whirling arm test facilities following the aircraft industry. However, the whirling arm test facilities are unfit to replicate the actual movement of the blades under rainfall. As the whirling arm facilities pretend to replicate aviation components, eg, the airplane wings, blades of helicopter, etc., the drop impact happens horizontally, but the wind blades present raindrop impacts more complex depending on the position during the rotating, eg, when the blade is on the top of rotating, the impact of the raindrop is along the leading edge in direction to the rotor. Therefore, the development of rain test facilities which replicate more consistently the direction of impact should be a priority for wind industry, eg, Sterling⁹³ for Boeing has developed an open wind tunnel facility with blade samples that can be rotated.

Finally, all the rain test facilities fail in the capacity of providing useful information to the industries about the real erosion resistance of materials, coatings, or topcoats used as leading edge protection systems. The main reason for this incapacity is the poor correlation of the actual operation and environmental conditions with the artificially simulated rain in the test facilities. Moreover, models or parameters to correlate the characteristic climate of a specific location with the experimental conditions in erosion test facilities should be investigated to obtain results with the capacity of prediction for the wind industry.

All these issues, ie, the lack of correlation between the same kind of test facility, between different kinds of test facilities or between the experimental results and the field measurements, need to be approached if the research in rain erosion wants to become a useful scientific and engineering field for the wind industry.

3.3 | Variables for rain erosion

The ASTM G73⁶⁰ test standard determines that the erosion should be reported as a plot of the cumulative volume/mass loss or the mean depth of erosion versus the cumulative exposure time or the mean cumulative impingement for experimental tests using whirling arm or rotational devices. Traditionally, the cumulative mass loss versus cumulative exposure time (Figure 8) has been the preferential plot in the literature.^{88,89,94,95} Typical erosion behaviour is shown in Figure 8 where three progressive periods of erosion can be seen. The first, as it is indicated above, is the incubation period when no significant mass loss is found, and thus the surface material remains unaffected and no erosion occurs. The second erosion period begins when the erosion is initiated, and, during this second period, the mass loss follows an almost linear behaviour in increasing the exposure time to the drops. The final erosion period starts when, deviating from the linearity, the mass loss follows a random behaviour mainly due to the catastrophic damage that occurs. This representation of the erosion becomes very useful to qualitatively compare the erosion resistance of materials but only on a specific erosion test facility. Valaker et al²⁷ compared different polyurethane-based coatings for offshore wind turbine blades, but no conclusive results were obtained due to the lack of verifications in the experimental conditions. Also, Zhang et al⁹⁰ use this representation of the cumulative mass loss versus cumulative exposure time to compare the erosion resistance of steel samples that are coated with an epoxy primer followed by two different polyurethane-based topcoats. Although a significant difference between the topcoats was found, regrettably a clear reason of why this difference in the erosion behaviour is not provided.

Nevertheless, this traditional representation of the erosion is lacking of important information about the experimental conditions, eg, the impacting water on the samples per cycle. Therefore, some authors reported the erosion results taking into account the impacting water, eg, Seleznev et al⁹⁶ considered the mass of the impacting water on the sample surfaces and Mahdipoor et al⁹⁷ the volume of impacting water per unit of area of the sample surface. Although these methods of reporting the erosion clearly improve the method proposed by the ASTM G73⁶⁰ standard test and they allow to compare the results obtained using drops of different sizes, they are still missing other relevant information about the experimental conditions, eg, running time, impingement velocity of drops, speed of sample, impact frequency, etc. Therefore, a further analysis in this direction is encouraged to be carried out due to this fact also helps in the design of the wind turbine blades and how they operate facing

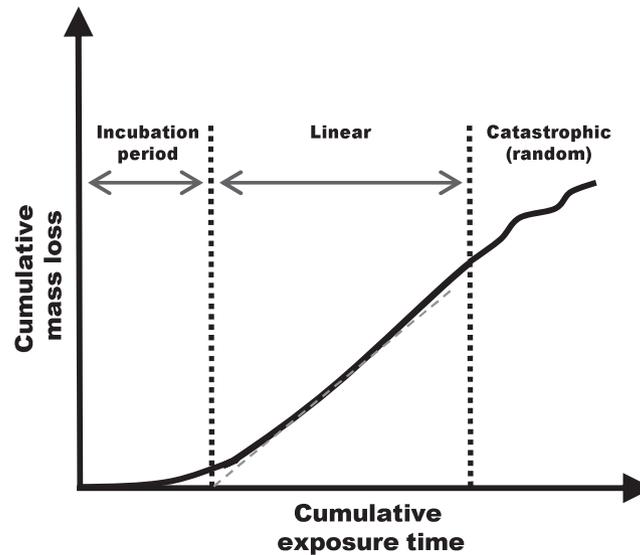


FIGURE 8 Typical erosion curve of cumulative mass loss versus cumulative exposure time

extreme precipitation events. Moreover, the development of more elaborated erosion variables with global information of the experimental tests could also help the experimental as well as computational studies on aerodynamic performance loss of wind turbines when erosion is featured. For example, Han et al.⁹⁸ quantitatively analysed the performance loss using computational fluid dynamics simulations where three levels of erosion, ie, light, moderate, and heavy erosion, were defined to carry them out. These levels were established depending on the erosion depth and width but without information of the rain and experimental conditions, ie, how long it takes to reach that level of erosion or under which conditions that has occurred. Therefore, parameters or variables of rain erosion providing more experimental information would enhance the comparison between aerodynamic performance loss studies and the overall conclusions on the aerodynamic performance of the wind turbine significantly.

4 | CONCLUSIONS

Research in the erosion on the leading edge of wind turbine blades is still an engineering field in development due to the complexity of the involved mechanical mechanisms and the lack of mature experimental techniques to analyse this damage. Therefore, for the purpose of establishing a framework with more scientific rigour, the following challenges should be approached:

- a. The necessity of more realistic simulated rains to carry out accurate experimental tests.
- b. The lack of standardisation for rain test facilities to compare the experimental results between rain test facilities.
- c. The development of rain test facilities where the test samples replicate the actual movement of the wind turbine blades.
- d. The definition of parameters or models to establish a correlation between the test time and the working time of wind turbine blades.
- e. The demand of models to correlate the climatic conditions on a specific site and the experimental conditions.

The success of dealing with one or some of these challenges will bring more ability to understand the rain erosion on the leading edge of wind turbine blades. Moreover, it will enhance the capacity to provide useful information for the wind industry to continue with its development.

ACKNOWLEDGEMENTS

The authors would like to thank the financial support for this research from ADEM, A green Deal in Energy Materials of the Ministry of Economic Affairs of The Netherlands (www.adem-innovationlab.nl).

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How to cite this article: Bartolomé L, Teuwen J. Prospective challenges in the experimentation of the rain erosion on the leading edge of wind turbine blades. *Wind Energy*. 2018;1–12. <https://doi.org/10.1002/we.2272>