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Review on Erosion Wear Subjected to Different Coating Materials on Leading Edge Protection for Cooling Towers and Wind Turbines

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Abstract
In response to the increasing importance of sustainable engineering solutions, this review focuses on evaluating the sustainability of different coating materials to solve erosion problems on the fan blades of a cooling tower and wind turbine. This review focuses on the types of erosion wear namely on the leading edge of cooling towers and wind turbines (LECT/WT) which will prioritise on the leading edge protection (LEP) on the fan blades used in various applications. This review will highlight recent works done on the design and development of high-efficiency cooling towers. The investigation on erosion resistant coating materials will also be reviewed since there are numerous claims made that certain coating material happen to provide enhanced resistance to erosion wear on LECT/WT. We reviewed all possible aspects of coating material on LECT/WT using different chemical composition namely to provide an optimum wear resistance to cast iron. In summary, there is no any specific coating material than can provide an infinite life span of a fan blade used in cooling towers or wind turbines. Lastly, we highlighted crucial future research on the aforesaid topic which may open new research pathways in the future. The 'hunt' for the so called 'ultimate' coating material to cast iron used in the LECT/WT is yet to be discovered.

Keywords Erosion wear · Leading edge of cooling towers/wind turbines · Leading edge protection · Coating material · Silicon · Cast iron · Fan/turbine blades · Future research

1 Introduction

The need for higher safety standards has become increasingly clear in high rotational speeds of technical components, such as engine blades, axles of high-speed trains, cooling towers and wind turbines. These critical major components face problems during operation, such as foreign object damage (FOD) from sand, birds, metals, water droplets, and other factors that can directly jeopardise both equipment and aviation safety [1]. In fact, the leading edge of a blade is usually the first place where these erosion problems occur, as the air or fluid flow makes the leading edge the largest contact area with foreign objects that cause FOD [2]. One of the biggest problems in the countries where cooling towers and wind turbines are operated is the erosion of the leading edge of the cooling tower blades due to rainfall. This problem poses a challenge in terms of maintenance costs and efficiency. To this end, a statistical precipitation model has been developed that describes the probabilistic distribution of critical rainfall parameters for a site-specific leading edge of cooling towers and wind turbines (LECT/WT) assessment [3].

Erosion of turbine blades leads to operational and structural problems, which emphasises the importance of erosion-resistant coatings. The erosion of the LECT/WT is a major challenge in the wind energy sector and causes considerable costs for inspection, maintenance, and production losses. The trend towards larger turbines with longer blades and higher tip speeds further exacerbates the LECT/WT problem. While efforts to understand rain-induced erosion include simulations and laboratory testing, a thorough

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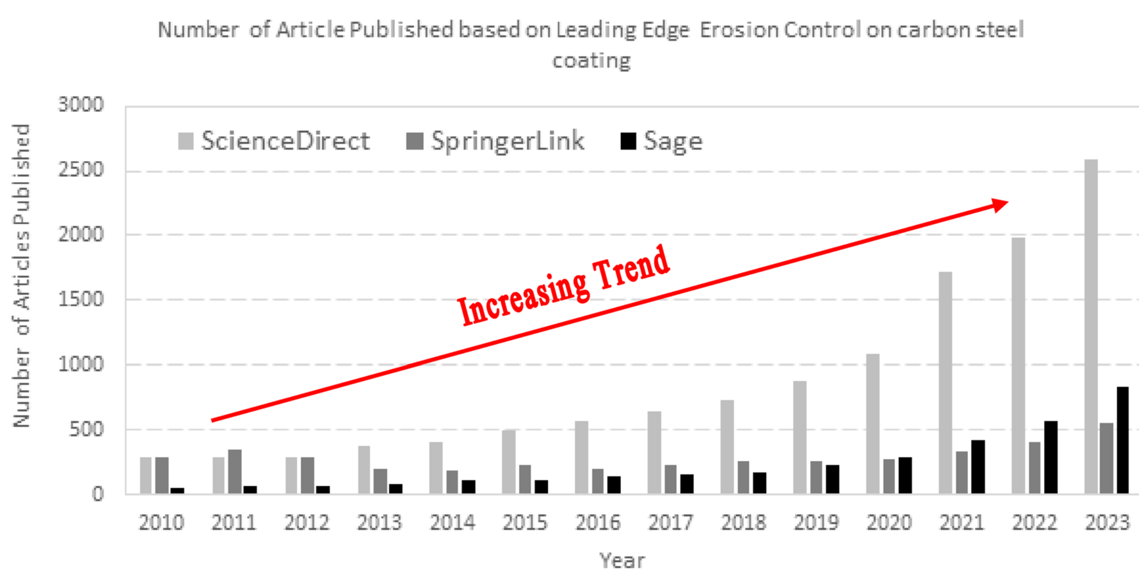
understanding of rain erosion on cooling tower blades is lacking. The industry standard for durability testing namely the vortex arm rain erosion test (WA-RET), reflects real operating conditions only to a limited extent.

Blade and turbine manufacturers and coating suppliers are actively developing leading-edge protection (LEP) structures: however, the durability of the latest inventions has yet to be proven [4]. In the context of rain erosion on cooling tower blades, the VN curve is usually used, where the impact velocity (V) is used instead of the stress. Expressions for service life vary from time to failure to specific impacts per area, making it difficult to correlate rain erosion tests with field data. Traditional approaches, such as the Springer model, are used to determine erosion resistance based on fatigue parameters [5]. However, elastomeric coatings pose a challenge for accurate predictions, which means that site-specific conditions need to be considered in the modelling. Meteorological data, which considers factors such as wind speeds and droplet size distributions, are crucial for reliable fatigue life predictions.

Recent experiments highlight the influence of droplet size on rain erosion performance and underline the need for further modelling efforts to improve our understanding of this crucial factor [1]. In the last 2 decades, erosion caused by hydrodynamics has been a critical problem faced by many countries, especially those with large hydrodynamic energy potential, such as India and Nepal. The focus is on hydrodynamic turbine blades, which are essential components of hydropower plants, as well as the negative impact of silt erosion on their efficiency and maintenance costs [6]. Researchers have used surface modification techniques to find answers, with a focus on protective coatings to guard against erosion [3]. The proposed approach concerns the control of turbine blades during heavy rain events, focussing on reducing tip velocity and extending leading edge life [7]. The study looks at important things such as the effects of liquid droplet loading, fatigue, data from vortex arm rainfall erosion tests, rainfall parameters, statistical occurrence, and different turbine control strategies.

By examining the complexity of LECT/WT and considering turbine control as a potential solution, this paper aims to contribute valuable insight to the ongoing discourse on the coating material applied to the blade as LEP [1, 8]. In this regard, this paper will focus on the research and developments in erosion wear subjected to different coatings materials used in the LED of fan blades in a cooling tower [1, 3]. Over the past 13 years, the review of erosion in different coating materials has developed considerably. Intensive research has been carried out on LEP, such as ceramic coatings [4], epoxy resin composite coatings reinforced with fly ash cenospheres and short glass fibres [9]. Figure 1 illustrates the number of published articles on erosion wear subjected to synthetic and natural fibres composites over the last decade. It shows the increasing interest of global research in this topic.

In the second decade of the twenty-first century (i.e. year 2020 onwards as shown in Fig. 1), research was dedicated to the field of coating review. At the beginning of the twenty-first



Keywords Used: Leading Edge Erosion; Carbon steel coating; Erosion wear; Cooling towers; Wing turbines

Search Engines Used: Science Direct; SpringerLink; Sage

Fig. 1 Number of articles published on erosion wear subjected to different coating materials century, the focus was more on non-renewable sources such as glass fibres, especially for LEP. During this period, there were countless scientific studies on glass fibres as alternative sources for industrial applications. The phenomenon of interest in glass-based alternatives as potential materials for protection purposes, the authors, therefore, consider it appropriate to provide a compilation of review on different coating materials subjected to erosion wear in the context of the history and scientific developments. Due to the complexity of the different types of research done on erosion wear, this review will only focus on the erosion wear of carbon steel/cast iron subjected to different types of coating material applied to the latter to enhance its wear properties subjected to LECT/WT. The authors also found it important to review various types of cooling towers and wind turbines which was design and fabricated to cater different cooling applications. Lastly, this paper will provide future research pathways to aid with the development on the subject matter by future researchers and scientists.

2 Review on Published Works on Erosion Wear

2.1 Characterization of a CrN/Cr Gradient Coating Deposited on Carbon Steel and Synergistic Erosion–Corrosion Behaviour in Liquid−Solid Flow Impingement: November 2023 [10]

This research was conducted to investigate how to enhance erosion resistance on carbon steel in complex conditions such as different climate conditions, and aerodynamic collisions with big particles. The work focussed on the double-annealing plasma alloying technique used to employ or deposit carbon steel. It helped to evaluate the cross-sectional area of the microstructure of carbon steel and the residual stress of the coating. The coating used was identified by three different layers: CrN layer, Fe–Cr–N diffusion layer, and Fe–Cr layer. The CrN layer consists of CrN-phase metal phases, which include ferrum. The total thickness of the coating is approximately 32.58 µm with three layers of it. The gradient structure of the coating reduces the deformation of the mismatches, enhancing the damage tolerance. The outcomes showed that the layer protected the part with an analysis of 868 MPa of compressive stress with no evidence of creep pores.

2.2 Effect of 3.5% NaCl Solution with Different Na2S Concentrations on Ultrasonic Cavitation Erosion Behaviours of HVOF Sprayed WC-Ni Coatings: December 2023 [11]

The study looked at how well WC-10Ni coatings made by HVOF spraying worked in ultrasonic cavitation erosion in both distilled water and a 3.5 wt% NaCl solution with different amounts of Na_2S (0, 20, and 200 ppm). Ziyu Wei and the team reported that there was evidence of correlation between the cumulative volume loss of the coating and the Na_2S concentration in the medium, indicating an increased cavitation erosion resistance with increasing Na_2S concentration. The observed improvement in performance was attributed to the growth of sulphide-enriched corrosion product films. When coatings were subjected to cavitation erosion in media with and without Na_2S, there was a big difference: when Na_2S was present, the formation of large craters and deep grooves on the eroded coating surface was slowed down. Ultrasonic cavitation damage to the coating was shown by the metal binder phase (Ni) breaking apart and the hard phase (WC) coming to the surface. This research sheds light on the protective effect of Na_2S in mitigating cavitation-induced damage and highlights the importance of considering environmental factors when optimising coating performance.

2.3 Comparative Tribological Performance and Erosion Resistance of Epoxy Resin Composite Coatings Reinforced with Aramid Fibre and Carbon Fibre: September 2022 [12]

In this study, chitosan-modified aramid fibre (MAF) and carbon fibre (MCF) were made by letting the chitosan stick to the fibres, followed by self-assembly. The change that happened made the adhesion strength between the fibres and epoxy resin much better. This is because active groups were on the chitosan-coated surface afterwards. It is worth mentioning that the interfacial stress strength (IFSS) of the MAF/EP and MCF/EP composites was 15.61 and 18.06% higher than that of the pure composites. A full study of how MAF and MCF affect the tribological performance and erosion resistance of the composite coatings was part of the investigation. The tensile strength of the MCF/EP composite coating surpassed that of MAF/EP by 11.09%, emphasising the superior load-carrying capacity and strength of MCF/EP. The anti-wear ability of the MCF-reinforced epoxy composite coating outperformed that of MAF, leading to a notable 66.35% reduction in wear rate compared to MAF/EP. In addition, the higher load-capacity and interface stress strength of MCF contributed to significantly improved erosion properties, resulting in a 50.38% reduction in erosion volume compared to MAF/EP. This exceptional erosion resistance was attributed to the high-strength characteristics of carbon fibre, effectively resisting SiC particle-induced erosion. The results show that chitosan-modified carbon fibre has a lot of potential to improve the mechanical and wear-and-tear properties of composite coatings.

2.4 The Increasing Importance of Leading-Edge Erosion and a Review of Existing Protection Solutions: November 2019 [13]

The research was carried out based on various types of protection, such as gelcoats, flexible coatings, leading edge tapes, and metallic erosion shields, which can help to emphasise the requirements for effective erosion-resistance in various environmental conditions. The experiment carried out by Robbie Herring and his team observed that gelcoats and flexible coatings have a heavy reliance on manual procedures during production and application. This manually increases the risk of defects, potentially serving as an initiation point for leading-edge erosion. The gelcoat, which has a similar material to the matrix material, specifically epoxy, plays a role as the first layer of the coating layer with a fibre laid on top. By mixing up the fibre and the resin, there is a chemical bond between the gelcoat and the matrix material. Then the layers were approached by another layer of flexible coating, such as polyurethane, which helped to provide a smooth surface for optimised coating results. Gelcoats are basically brittle and have a high acoustic impedance. On the other hand, flexible coatings are more ductile and have low impedance. But it showed up with high strain failure rates and stress reduction on the impact surface. Similar characteristics were discovered on the leading-edge tape, which is high-flexibility, low impedance, and ductile to dampen the initial impact of raindrops that cause the deformation. Besides, erosion shields are either rigid or semi-flexible and are affixed in different pieces using adhesive. Being thicker means that the shockwave of the raindrop is extended and dissipated further compared to tapes and coatings, which also reduces the transmission damage to the rigid composite blade, which prevents the cavity from being damaged by the shockwave.

2.5 Particle and Rain Erosion Mechanisms on Ti/TiN Multilayer PVD Coatings for Carbon Fibre Reinforced Polymer Substrates Protection: February 2021 [14]

In the conducted study, physical vapour deposition (PVD) coating is the major study objective for erosion protection on carbon fibre-reinforced polymers. The PVD used is known as titanium/titanium nitrite (Ti/TiN). This kind of coating was stacked together through DC magnetron sputtering with a thin layer, which started in a range of 1.5–11 µm. Borja Coto et al. found that thin coating plays an important role in helping to prevent delamination when carbon fibre faces sand erosion. On the other hand, the thick coating has better resistance to substrate-driven erosion. These results showed that thin and hard tribological coatings such as TiN, TiAlN, CrN, and CrAlN have a high potential for advanced erosion control, which can lead to the laminar-to-turbulent issue and impact aerodynamic properties. These coatings were tested for sand and rain erosion that is commonly faced by offshore industries by examining failures in mechanisms with different coating thicknesses. Rain erosion and sand erosion showed different kinds of trends in the erosion behaviour, which depends on the thickness of the coating layer. Thin coating shows a better result during rain erosion compared to thick coating.

2.6 Assessment of the Rain and Wind Climate with Focus on Wind Turbine Blade Leading Edge Erosion Rate and Expected Lifetime in Danish Seas: April 2020 [15]

This review is based on an investigation of leading-edge erosion that happens at offshore wind farms in the Danish Seas. This happened in the year 2020, when the offshore area faced extreme weather conditions such as heavy rain and high wind conditions which cause an impact to leading-edge erosion. The model showed eight different results of erosion during that time, and the average lifespan of those fans was estimated to be approximately 3 years. The research conducted by C. Hasager and co-partners showed that relative profit saved a cost in the range of 2.8–4.8% from erosion control. From the data, it shows the result based on 16 years of study at the Danish Meteorological Institute weather station in Denmark, which shows the turbine blades at inland stations have a longer lifespan range of 3–13 years, while coastal stations only have a range of 3 years. The kinetic model of the inland station was three times higher than that of the coastal station. The speed limitation of the blade is approximately 42 m/s, and the kinetic energy model shows a maximum profit increase of 3.1% at the threshold of 4.8 mm/h. The two inland sites displayed an average erosion rate of 0.08/year, damage per rain of around 0.13 m per year, and 12.7 years of lifetime, while the coastal station displayed a result of 0.33 erosion rate per year, 0.57 m per year, and lifetimes of 3.2 years. The coastal station's corrosion rate is way higher than that of the inland station. In summary, the authors concluded that extreme weather conditions subjected to LECT/WT can shorten the life span of the offshore farm wind turbines.

2.7 A Probabilistic Rainfall Model to Estimate the Leading-Edge Lifetime of Wind Turbine Blade Coating System: November 2021 [16]

In the study conducted by Amrit Shankar Verma and team, it illustrates data with higher accuracy, real-scale blade coating, and lifetime estimates from a probabilistic rainfall model. This model was established to show the critical rain parameters' probabilistic distribution in a static way based on 2 years of onshore rainfall data with a new droplet size distribution (DSD). The outcome demonstrates the data from inland and coastal sites in the Netherlands. The impact between the rain and the high-speed blades is around 70–120 m/s, which leads to an issue of pitting and roughening of the leading-edge surface. This various type of damage will be the main cause of fatigue failure of the coating and structural damage. Leading-edge erosion in the aero-foil section increases the drag coefficient above 314% and decreases the lift coefficient below 53%, which results in an obvious reduction of aerodynamic efficiency in the turbine blade. The analytical surface fatigue model was proposed to be present on a 5 MW turbine with a hub height of 90 m. It was found that 88% of inland sites have greater erosion resistance based on 50-year hourly data while comparing the De Bilt inland site and the De Kooy coastal site. The coastal site showed a light rainfall condition of ($I<2.5$ mm/h) with a dominance of droplet size less than 0.6 mm, and this helped the rainfall model to be highly sensitive in this research. The expected lifespan of coastal site coating is 1.2 years less than that of inland site coating, which is 4.2 years. This proves the high erosion rate of coastal sites from a probabilistic rainfall model analysis.

2.8 Erosion Behaviour of Pulsed-Jet Test Facility for Wind Turbine Blade—February 2023 [17]

This study was conducted by Yamagata et al. to investigate the erosion behaviour of aluminium in a jet pulsed-jet erosion facility, which can help simulate the wind turbine condition. The facility utilises a liquid slug to simulate different droplet behaviours, which will play a role in differentiating the characteristics of various erosion behaviours by measuring the jet-slug velocity and volumetric material loss at various jet velocities. This complexity arises from the different droplet diameters, target materials, and impact velocities. The recent concern about erosion on wind turbine blades essentially has a droplet diameter of approximately 2 mm with an impact velocity ranging from 60 to 100 m/s. The erosion testing facility used is a pulsed-jet erosion test, which utilises a rotating disc to interrupt the continuous liquid jet as a simulation of rain erosion with a liquid slug. This helped to illustrate various types of erosion and variation between pulsed jet and whirling arm tests. The nozzle exit velocity was measured to have a 20% higher velocity than the impact velocity, while the droplet used was measured to be around 10 µm to mm, which means the impact of the revolving disc with holes was related to the disparity.

2.9 Solid Particle Erosion-Wear Behaviour of Cr_3C_2–NiCr Coating on Ni-Based Superalloy: March 2017 [18]

Hongwei Zhang and his team studied on the exploration of erosion-wear behaviour of, Cr_3C_2–NiCr which is a nickel-based superalloy coating for flue gas turbine blade protection. Besides, the main objectives of depositing the coating on the turbine blade are to investigate the air pressure, impingement angle, erosion temperature, and particle size in the mechanism. These factors are the common erosion issues faced by industries such as petroleum, chemical, aerospace, and power plants, which have caused significant economic losses. Nickel-based superalloys are a common material used in these industries, especially in flue gas turbines. It faced erosion wear from high-temperature flue gas catalyst particles, leading to fatigue performance degradation. The coating used on the nickel superalloy was deposited using a high-velocity oxygen-fuel spraying technique with a concentration ratio of 75 wt% of -3, -2, and 25% of -2. There are few studies that have explored the erosion resistance of a nickel-based superalloy coating on nickel-based superalloy substrates, and it was found that it is able to resist combined erosion–corrosion damages at flue gas temperatures up to 600 °C. Besides, it was found to have a higher volume erosion rate when the air pressure increased, accompanied by an increase in the number of depths of each pit on the coating surface. Then, the volume wear rate of the coating material increases when the coating thickness decreases. When the coating thickness surpasses the value of 120 µm, the variance in wear rate is negligible. After that, it was observed that the blade has better erosion resistance at a 90° impact angle than a 30° impact angle, and it displayed a peak erosion rate at a 60° impact angle since this blade became the most ductile and brittle blade in a test. The results suggested a sustainable and high-temperature erosion-resistant coating.

2.10 Rain Erosion of Wind Turbine Blades: Computational Analysis of Parameters Controlling the Surface Degradation: November 2019 [19]

In the study, Saeed Doagou-Rad and Leon Mishnaevsky Jr. utilised a systematic finite element simulation approach to assess the influence of different parameters on erosion resistance performance under rain contacts. The finite-element simulation was used to analyse the high-speed rain droplet scenario, including miscellaneous droplet size, speed, and incident angle, which are also important to study in terms of stress behaviour and coating lifespan. This simulation illustrates the investigation of environmental parameters, design parameters, and manufacturing parameters. Environmental parameters show the factors related to the external conditions affecting erosion performance. Design parameters display the aspects associated with the design of wind turbine blade tips impacting different particles, and manufacturing parameters demonstrate the parameters related to the production processes influencing erosion performance. Besides, the finite-element simulation method and the parameters play an important role in identifying various coating material characteristics, such as stiffness, viscoelastic properties, and Poisson's ratio, for effective protection against rain erosion. Moreover, the critical importance of surface properties, manufacturing aspects, and droplet shape in estimating coating lifetime through a numerical simulation will also be one of the key findings. Furthermore, the results show that perpendicular droplet contacts are the most critical scenarios for damaging the blade. It was also proven that the lower stiffness and Poisson's ratio led to lower stress levels. Then, by increasing damping, enhanced stress dissipation during droplet contacts and viscoelastic properties shifted high-stress locations from the top surface to secondary-surface regions, altering damage patterns. Another double-coating investigation by the researchers revealed that the maximum stress was defined by the top layer of coating, while positioning a compliant layer as a substrate led to elevated stress, especially at the interface. The authors suggested to avoid the debonding between the coating and the properties since it requires maximising the top coating thickness.

2.11 Modelling of Water Droplets Erosion on a Subsonic Compressor Cascade: November 2019 [20]

Within the realm of academic research, the efficiency of the compressor plays a critical role in leading the performance of gas turbines to achieve optimal efficiency. But the blade fouling caused by dust, dirt, and droplets has contributed to a performance deterioration for the compressor. Certain instances of blade fouling result in irreversible losses since the blades cannot be recovered. Compressor fouling is the cause of up to 85% of the performance loss in turbomachinery. Certain instances of blade fouling result in irreversible losses since the blades cannot be recovered. Compressor fouling is the cause of up to 85% of the performance loss in turbomachinery. Accurate prediction of water droplet erosion is vital for machine design and maintenance evaluation, as it facilitates the enhancement of maintenance programmed scheduling and administration, ultimately leading to improved turbomachinery performance. Consequently, P. Venturini et al. have constructed a predictive model for water droplet erosion on surfaces composed of stainless steel. In the simulation configuration, 50 µm of droplets or particles was injected into the inlet of the compressor blade. All examined models give accurate information on hit sites and stored energy, as demonstrated by the results. Furthermore, substantial variations were identified in the prediction of degraded materials. Three models were used to compare to each other which are the Springer et al. model (1974), Tabakoff et al. model (1979), and the Author's model. Water droplet erosion is not fully understood since the simulations are not well established. Springer et al. model (1974) demonstrates an unrealistically prediction with a large erosion area compared to others. But the same factor to be considered in this simulation data is the water droplet erosion depends on various factors: impact velocity, angle, droplet, droplet size and the surface material. Although there is a lack of accuracy or unreliable data, all models provided the same information which are the impacts, accumulated energy, and zones susceptible to erosion.

2.12 Effect of Oblique Stator on the Aerodynamic Performance and Erosion Characteristics of Governing Stage Blades in a Supercritical Steam Turbine: February 2019 [21]

In the context of scientific research by Liuxi Cai and the team, solid particle erosion poses challenges for supercritical scenarios in power generation industries since it causes huge impact in safety, and also the efficiency of a turbine. It was highlighted that solid particle erosion reduced approximately 3% of efficiency in aerodynamic performance and 2.16% of unit efficiency under part load operation. In this case, hard coating technology is one of the effective solutions to solve this kind of problem by extending the lifespan of a blade. To minimise the rate of erosion, studies on trailing edges, employing end-wall countering, and introducing an oblique stator are necessary. It is known that the oblique stator structure can lower erosion losses in the turbine cascade. Therefore, a particle tracking model was established to control the stage cascade of a supercritical steam turbine by utilising the high-temperature erosion modelling studies. This model investigation is focussed to analyse the steam-particle flows and to imitate the impact of an oblique stator on aerodynamic performance and erosion characteristics of governing stage blades. The exploration showed the load position was shifted to be maximum towards the nozzle trailing edge while the nozzle oblique angle increased. The authors claimed that by increasing the oblique angle lead, the secondary flow loss in cascade and the stage efficiency increases by 0.8, 0.35 and 0.44% at oblique angle of 15°, 30° and 45° respectively. This has proven the erosion resistance of a blade can be improved by the optimal oblique angle and enhanced aerodynamic performance in the governing stage of a supercritical steam turbine.

2.13 Leading Edge Erosion of Wind Turbine Blades: Understanding, Prevention and Protection: May 2021 [22]

Within the framework of scientific investigation, various strategies were proposed to counteract leading-edge erosion. The research was based on a case study of Danish Energy Company blade erosion repair at the Anholt Offshore Wind Farm in 2016. The blade surface erosion of wind turbines is a substantial obstacle that impacts the progress of wind energy development. Therefore, Leon Mishnaevsky Jr. and his team provided an overview of recent studies on mechanisms, modelling, and prevention of surface erosion from multiple perspectives, such as meteorology, aerodynamics, material science, and computational mechanics. The mechanisms and modelling illustrate the understanding and prediction of erosion processes. Then experimental resting was used to test anti-erosion coatings such as epoxy, polyurethane, and Ever Lasting Leading Edge (ELLE) soft shell developed by PolyTech. [18] The authors also explored on the aerodynamic impact of leading-edge erosion on the wind turbine and investigated the surface roughness of the blade due to erosion and meteorological aspects, which included precipitation parameters, characteristics of rain and hail, and regional variations. The current direction of anti-erosion coating was then displayed in a computational model where the prediction was made. Mechanisms ranging from meteorological and geographic conditions to the mechanics of polymer chains and the formation of material nanostructures had great influence on the LECT/WT.

2.14 Modelling and Monitoring Erosion of the Leading Edge of Wind Turbine Blades: November 2021 [23]

The purpose of this research is to design and implement an innovative micro-electro-mechanical monitoring system that specifically targets aerodynamic surface pressure and aero-acoustic data on wind turbine blades. The study presents a methodology for simulating and diagnosing erosion, particularly LECT/WT, on wind turbine blades, which is inspired by the Aero-sense project. Furthermore, to investigate the environmental impact on the blades, environmental elements such as moisture, temperature variations, ultraviolet radiation, and impact from raindrops, sand, or hailstones were included to contribute to LECT/WT. The researchers utilised a monitoring system that employs a deep-learning multivariate time-series-based transformer and a stochastic spatiotemporal erosion model to evaluate erosion occasions. Differential inflow and erosion-induced aeroelastic responses are simulated by the linked model. The group used a random set of decaying air foil aerodynamic polars and a non-homogeneous compound Poisson process in a wind turbine blade erosion model that considered space and time. Then, on-blade sectional monitoring data are used to change a deep-learning transformer model with attention mechanisms so that it can find and group slow, long-term leading-edge erosion processes. To find out how erosion affects the dynamic turbine response, aero-servo-elastic models use a random set of degraded air foils aerodynamic polars that are made from numerical experiments. The deep-learning attention-based transformer could help with efficient wind farm maintenance planning by accurately detecting slow deterioration processes using long time series inputs. By directing attention towards distinct features at different time intervals, the attention mechanism improves the accuracy of predictions. This is especially advantageous when dealing with long-term series sequences that depict gradual degradation, which makes it suitable for spatiotemporal problems with extended time horizons.

2.15 Recent Developments in the Protection of Wind Turbine Blades Against Leading Edge Erosion: Materials Solutions and Predictive Modelling: October 2023 [24]

The increase of wind energy, particularly offshore wind, is a crucial component of renewable energy and has become a global trend, which makes it more challenging due to higher mechanical and environmental loads. In recent years, leading-edge erosion has become not only the most frequently observed damage but also the most critical and expensive damage due to the degradation mechanism that requires frequent repairs and maintenance. There are a lot of parties that want to solve this problem to increase the efficiency of a turbine. The most popular existing solutions include products from businesses such as LM Wind Power, Siemens, 3 M, Bergolin, Duromar, Enercon, Poly Tech, and Hempel. Irrespective of the existence of potential remedies, leading edge erosion continues to be a significant concern, especially with larger blades that travel at greater tip speeds in areas prone to heavy rainfall and hail. Therefore, the recent review is still focussed on anti-erosion coating, new materials, and computational modelling of erosion. The study combines observations from annual symposia on wind turbine blade degradation that DTU Wind has been hosting since 2020. Most common coating materials are being developed in the direction of thermoplastic and hybrid thermoplastic coatings, high viscoelastic coatings, structured interfaces to enhance coating attachment that involve hybrid fibrous layers, polymer brushes, or interphase layers, electroforming metallic leading-edge erosion shields, and structured nano-reinforced coatings.

2.16 Introducing a Data-Driven Approach to Predict Site-Specific Leading-Edge Erosion From Mesoscale Weather Simulations: February 2023 [25]

Jens Visbech and his team realise that while conventional engineering models, like the Springer model, are widely employed, alternative modelling approaches that incorporate field data are necessary for advanced research in leading-edge erosion. Therefore, this article introduces a data-driven approach for simulating erosion damage based on mesoscale numerical weather prediction (NWP) models and blade inspections from wind farms in northern Europe. The framework makes use of machine learning-based models, especially feedforward artificial neural networks with ensemble learning, for reliable training and validation. The model used by the author is based on a twofold workflow and training application. During the training process, the user provided a time series of mesoscale weather data, blade inspection data, and wind turbine parameters that were consistently inspected in a windfarm. The model determines the accumulated impact of the wind turbine by integrating wind speed, precipitation frequency, and turbine attributes. The internal model's input and target are observed defects from blade inspections that are classified and ranked for both initial and cumulative damage. In order to estimate erosion damage, the user uploads new meteorological data and turbine parameters for either newly constructed or existing wind farms during the application process. With flexibility dependent on user data, the model produces site-specific damage projections that may be displayed as an interactive erosion map. The validation results indicate that mean predictions and observations are in good agreement, except for a modest underestimation of damage in general, over 0.25 of 5–7%. The ensemble error distribution has a bimodal pattern, which signifies the tendency to underestimate and underscores the significance of individual samples. The ensemble output is physically tested throughout variable space, which provides signs of model certainty and displays an incubation period. The research acknowledges the presence of assumptions and uncertainties pertaining to meteorological data, operational circumstances, and blade attributes. It underscores the model's function as a low-fidelity instrument that aids in the budgeting of maintenance costs and repair planning.

2.17 Rain Erosion Testing of Lightning Diverters—January 2011 [26]

The rain erosion circumstances associated with a typical flight profile are simulated by the Wind and Rain Erosion Rig; also known as WARER. A nominal rainfall rate of 25.4 mm is produced during the test at a test speed of approximately 178 m/s, which is almost the same as a calibrated airspeed of 300 knots at 10,000 feet under the International Standard Atmosphere (ISA) conditions. A revolving arm holding circular coupons with a diameter of 27 mm is situated 0.6 m away. The material's resistance to droplet impact determines how long the test will last. The arm is accelerated to speed before the droplet system is activated. To ensure testing uniformity and prevent early specimen failure caused by the diverter's exposure to high normal acceleration forces, elements provided by WARER were well calculated by the participating authors. At first, intervals were extended to two minutes instead of one minute. The actual precipitation rate observed during testing is around 72% of the stipulated 25.4 mm/h, which can be attributed to a decrease in rotating speed from the peak value of the turbine blade. It is crucial to account for this reduction when comparing outcomes to those of other tests, and it indicates that the time to failure should be modified to around 0.72 units from its initial value. The specimens manufactured by WXGuard showed a significant enhanced resistance to rain erosion in simulated rainfall circumstances when compared to test specimens L1–L5, with a testing duration of 18 min, which was four times longer than the 3-min duration recorded by three of the competitor specimens. The WXGuard specimens W4 and W5 failed the normal acceleration test in response to the applied forces. It demonstrates that droplet impacts were the primary impact of the damage. The specimens exhibited a normal acceleration of $27.6 \times 10^3\,\mathrm{m/s^2}$, and the evolution of damage transpired at intervals corresponding to droplet hits.

2.18 Effects of Leading-Edge Erosion on Wind Turbine Blade Performance: October 2014 [27]

The study aims to test a wind turbine air foil with shape changes that simulates leading edge erosion at different stages of development. The surface erosion model is based on observations of eroded blades during operation and repair. The goal is to develop a fundamental understanding of aerodynamic effects, quantify the impact of different types and magnitudes of erosion, and evaluate the need for erosion mitigation strategies. The authors simulate leading edge erosion based on a DU 96-W-180 air foil. The wind turbine erosion model was recorded through observation and photography to examine the developmental stages of leading-edge erosion, including small pits, ruts, and delamination. The shape changes were used to accurately model the "negative" erosion on an actual wind turbine. The different types of relative impacts and magnitudes of leading-edge erosion on blade performance were then quantified to assess the potentially detrimental effects of leading-edge erosion and determine the need for erosion mitigation strategies. In addition, bug strikes were simulated on the leading edge, and a significant negative impact on the performance of the wing was observed. The leading-edge erosion showed that the drag increased by 6–500% and a significant reduction in the lift coefficient was observed at higher angles of attack, highlighting the degradation of the air foil's performance. By analysing PROPID (i.e. a computer program for the design and analysis of horizontal axis wind turbines), the authors estimated an 80% increase in drag, resulting in a 5% loss of annual energy production. However, it was found that the lift increased by 400–500% and the loss of annual energy production increased up to 25%.

2.19 Leading Edge Erosion Detection for a Wind Turbine Blade Using Far-Field Aerodynamic Noise: May 2023 [28]

As for the methodology of scientific research, Yanan Zhang and his team have explored on the effects of leading-edge erosion on the aerodynamic performance of wind turbine blades and developing an economical, adaptable and reliable damage detection method for real-time monitoring. They investigated the effects of erosion on aerodynamic noise and the ability to detect damage. Most of the previous studies focussed on aerodynamic performance. The authors decided to focus on real-time monitoring in addition to predicting power output and mitigating operational risk. An experiment was conducted with a DU96 W180 air foil equipped with different degrees of erosion on the leading edge to investigate the physical interpretation of the aerodynamic noise characteristics associated with different degrees of erosion (pits, furrows, delamination of the coating). They found that erosion on the leading edge usually starts with small holes and then widens into larger furrows that lead to delamination of the coating. Current detection methods often use vibrations, strains, and elastic waves, which requires the installation of sensors inside the blade. Therefore, non-contact methods such as infrared thermography and laser scanners are being researched. Active and passive airborne sound-based approaches are also being considered for further investigation. The analysis also shows that at low erosion severity, the clay peaks are like those of clean falls, although their amplitudes are larger. By shifting the sound peaks to higher frequencies with reduced amplitudes, moderate erosion indicates altered flow characteristics. Broadband sounds emanating from both sides of the blade during periods of severe erosion indicate the transition to turbulent flow. With turbulent inflow, the impact noise at the leading-edge decreases compared to the initial situation at medium–high frequencies, while the noise at the trailing edge shows no difference with or without erosion. This method demonstrates effectiveness in both smooth and turbulent flows, with the noise spectra differing significantly depending on the extent of erosion. Detection is performed over a range of flow velocities and angles of attack, with delamination being the most prominent feature.

2.20 Investigation on Aerodynamic Noise for Leading Edge Erosion of Wind Turbine Blade: September 2023 [29]

Hongyu Wang and Bin Chen addressed issues in acoustic-based erosion detection. They used computational fluid dynamics (CFD) to investigate the aerodynamic noise mechanism of damaged wind turbine blades. CFD utilised the zonal detached eddy simulation model to simulate a three-dimensional turbulent flow environment. Then, the length and depth of the leading-edge erosion were simulated based on the 5 MW National Renewable Laboratory wind turbine. Besides, they found the erosion had caused uneven pressure pulsation near the leading edge and the tip, which increased the region of airflow separation and caused the separation point to move ahead. This also explained why the eroded blade has a higher acoustic level than a normal blade. After that, the investigation specifically mentioned that erosion had caused a noticeable imbalance in the noise pattern in both the upwind and downwind directions with a higher acoustic level.

2.21 Assessment of a Wind Turbine Blade Erosion Lifetime Prediction Model with Industrial Protection Materials and Testing Methods: June 2021 [30]

The work focussed on a study using rain erosion testing (RET); c.f. Figure 2 which was evaluated using the Springer model industrial LEP systems designed for wind turbine

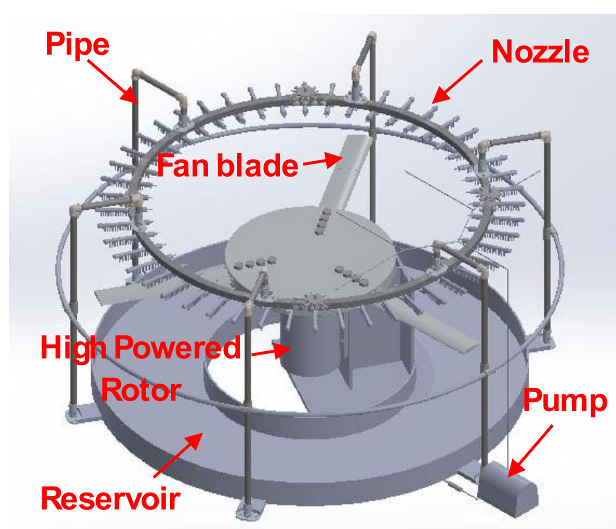


Fig. 2 Leading edge erosion blade coating testing unit [31]

blades. Tests were performed on coatings with varying thickness (120, 180, and 240 μm) under conditions simulating rain impact at a rotational velocity of 1000 rpm, corresponding to local impact velocities of 84–125 m/s. This simulated the real-world erosion conditions that turbine blades face, especially offshore. The study found that different layer configurations and thicknesses impacted the time to incubation (beginning of erosion) but not the overall erosion rate. These results provide valuable insights into how well the Springer model, initially based on aerospace data, can predict the erosion resistance of modern wind turbine blade materials, highlighting the need for adjustments in the model for accurate lifetime predictions in wind energy applications.

2.22 Engineered Anti-Erosion Coating for Wind Turbine Blade Protection: Computational Analysis: October 2022 [32]

The paper explores the development and potential of structured, reinforced coatings to enhance the erosion protection of wind turbine blades to investigate reinforced coatings to improve erosion protection and prevent surface degradation of wind turbine blades over time. The authors developed a multiscale computational model to simulate the impact of rain droplets on polymer coatings with internal structures. Besides, the researchers utilise the coupled Eulerian-Varangian (CEL) shown in Fig. 3. This approach uses the sub-modelling technique in a finite element model to determine local stress distribution in structured coatings. The analysis of wave reflection on particle reinforcement in coatings and stress concentration around voids were experimented through computational experiments system. Both fibre pulp-reinforced polymer coatings and graphene particle-reinforced coatings showed reduced stress concentration in voids and air bubbles compared to non-reinforced polymers. The stress shielding effect on voids, caused by the fibre pulp or disc particles reinforcement, could significantly extend the lifetime and performance of anti-erosion coatings. The developed multiscale computational model demonstrates the effectiveness of fibre Experimental setup for rain erosion-resistant coatings for wind turbine blades pulp and graphene particle reinforcement in reducing erosion, which often initiates near voids in coatings.

2.23 A Novel Solution for Preventing Leading Edge Erosion in Wind Turbine Blades: June 2021 [34]

The article by William Finnegan and team focuses on a cutting-edge LEP system that utilises thermoplastic polyurethane (TPU) due to its exceptional erosion resistance and mechanical qualities. The study included rain erosion testing, structural tests on a demonstrator, and full-scale

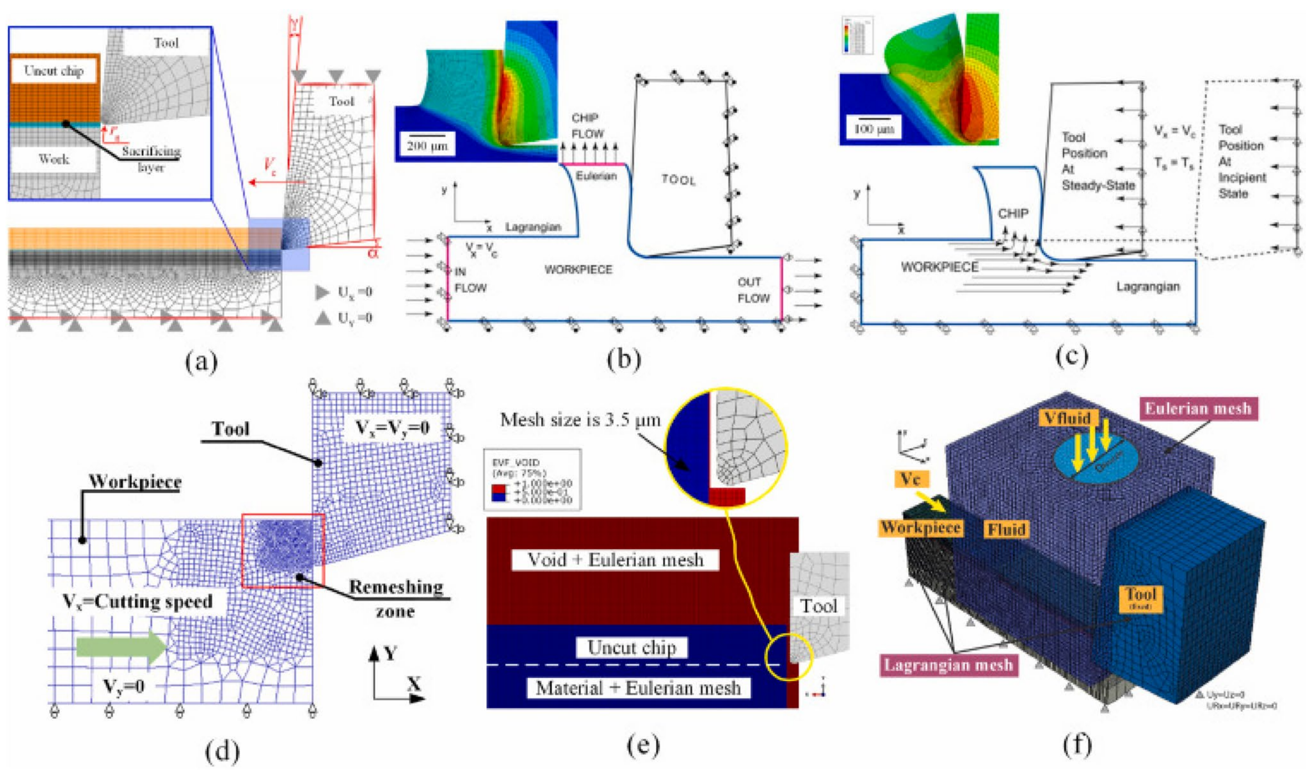


Fig. 3 Coupled Eulerian Lagrangian method [33]

tests on a wind turbine blade to evaluate the LEP's performance. The findings indicated that the LEP exhibited strong erosion resistance and retained its structural integrity in several scenarios, resulting in reduced strain and improved blade protection. The subsequent stage entails conducting practical experiments in maritime environments, with forthcoming discoveries to be documented. Figure 4 shows the conceptual design for the rain erosion test device which complies based on ASTM G73-10 Standard Test. In a nutshell, the rain droplets determine the erosion rate of the given material, i.e. the higher the cavity formed, the higher the erosion wear of the material.

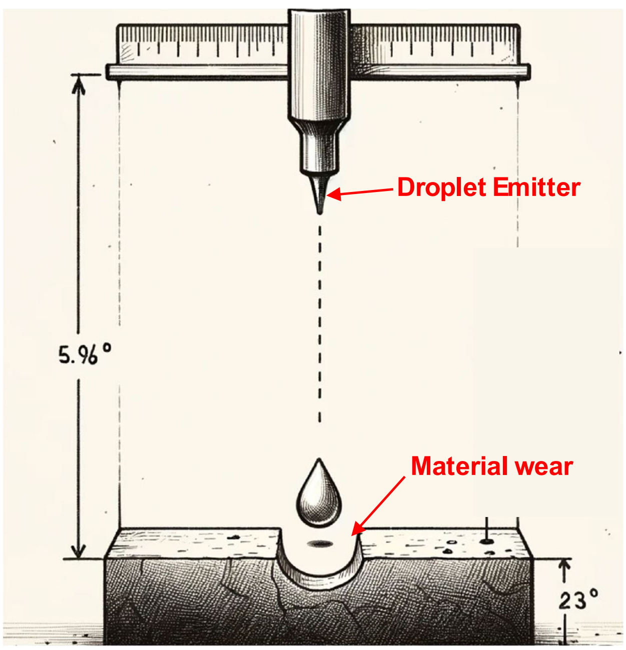


Fig. 4 Conceptual design of experimental setup rain erosion test [34]

2.24 Nanoengineered Graphene-Reinforced Coating for Leading Edge Protection of Wind Turbine Blades: September 2021 [35]

The study focuses on investigating the development and assessment of nanoengineered graphene-reinforced polyurethane coatings designed for wind turbine blades. The study conducted studies with three distinct coatings: unadulterated polyurethane (PU), polyurethane enhanced with graphene (PU + GNP), and a combination of graphene and sol–gel enhanced polyurethane (PU + GNP + SG). The single point impact fatigue tester (SPIFT) as shown in Fig. 5 was employed to assess the erosion resistance of different coatings. The experiment involved exposing the coatings to the impact of high-velocity nitrile rubber balls until they reached a state of failure. Measurements were conducted to ascertain criteria such as the point at which cracks begin, the beginning of delamination, and the quantity of coating material that is lost. The coating comprises of polyurethane (PU), glass nanoparticles (GNP), and superhydrophobic graphene (SG) provided the most effective resistance against erosion. The PU + GNP + SG coating displayed a substantially greater resistance to crack initiation, delamination, and material loss as compared to pure PU. The durability of PU + GNP + SG coatings exhibited a significant increase, with lifespans that were up to 13 times longer in comparison to non-reinforced PU coatings. Incorporating graphene and hybrid nanoparticles into polyurethane coatings significantly increased their erosion resistance. These discoveries have crucial significance for the advancement of future erosion-resistant coatings.

2.25 Innovative Leading Edge Protection System for Wind Turbine Blades: January 2020 [37]

The research by Aerox Advanced Polymers SL, focussed on addressing the significant issue of erosion in wind turbine

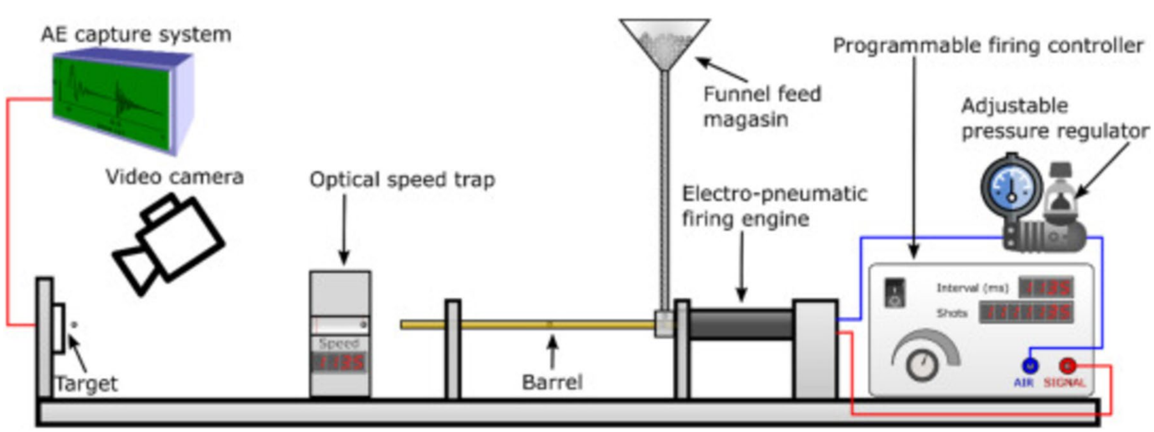


Fig. 5 The single point impacts fatigue tester (SPIFT) erosion testing setup [36]

blades. The project developed an innovative leading-edge protection (LEP) polymeric coating, utilising a novel blend of hybrid polyurea–polyurethane technology. This coating was designed to have exceptional mechanical and chemical resistance, tailored to withstand the harsh environmental conditions encountered by wind turbine blades. The researchers used scaling-up manufacturing and application processes for adjustments to the coating to facilitate large-scale manufacturing and application. Parameters such as adhesion, rain erosion performance, and sag resistance were rigorously tested and verified. Advanced material models were developed for predicting the coating's behaviour under various conditions. The technology was enhanced by modulating the polymer's molecular weight and adjusting its rheology, curing, and working times. The coating's viscoelastic behaviour allowed it to absorb high-speed, high-frequency impacts, such as raindrops, thereby reducing stress concentration points where erosion typically initiates. The project provided a deeper understanding of rain erosion mechanisms and their theoretical models, improving the correlation between test results and real-world working conditions of wind turbine blades.

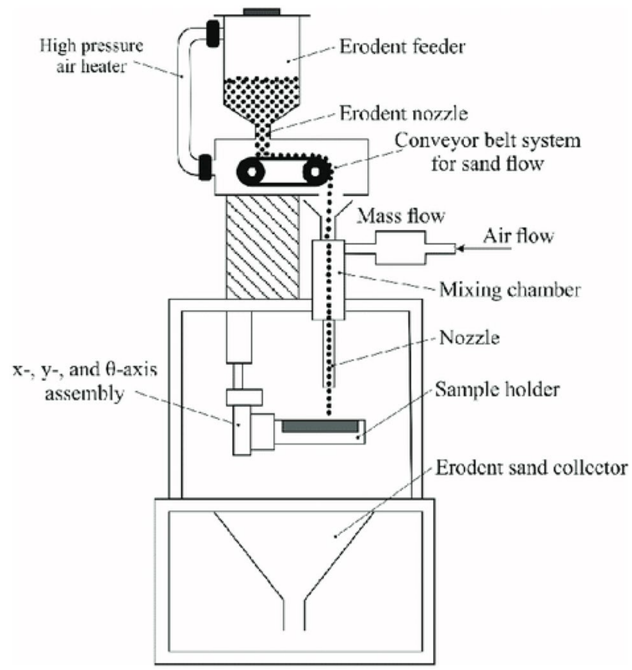


Fig. 6 Schematic illustration of the ASTM G76 setup [39]

2.26 Erosion Resistance Enhancement of Polymeric Composites with Air Plasma Sprayed Coatings: February 2023 [38]

The study centred on creating and assessing the effectiveness of an erosion-resistant coating for polymer-based composites utilising air plasma spray (APS) technology. Sina Mirzai Tavana and co-partners employed three distinct coating material such as tungsten carbide–cobalt (WC–Co), martensitic chromium stainless steel, and alumina-titania. The carbon/epoxy composites were used as the substrate. Subsequently, a stainless-steel mesh with a weave pattern and a mesh size of #200 was added to the composite material during the manufacturing process. This mesh was designed to safeguard composite fibres during grit blasting and heat spraying processes, while also enhancing the adhesive strength between the coatings and the substrate. Surface preparation and coating deposition were achieved by the utilisation of grit blasting and plasma spraying techniques. The outcome demonstrates that the flatwise tensile tests revealed a substantial enhancement in the bonding strength of the coating due to the specified processing parameters. Tests were performed to assess the resistance of solid particles to erosion using the air-jet erosion methodology according to ASTM G76 standard; c.f. Figure 6. In addition, measures of hardness were obtained for the coated samples. Coatings exhibiting brittle characteristics, such as alumina-titania, show enhanced resistance to erosion when applied onto rigid and durable substrates, such as mild steel. Coatings exhibiting ductile behaviour, such as martensitic chromium stainless steel, were found to be better suited for softer substrates such carbon fibre-reinforced composites. The incorporation of stainless-steel mesh into the composite substrate permitted improved adhesion and safeguarding during the coating process, resulting in heightened resistance to erosion.

2.27 Experimental Study on Erosion–Corrosion of Carbon Steel in Flowing Nacl Solution of Different pH: September 2022 [40]

The research aimed to investigate the characteristics of X65 carbon steel under various situations of pure corrosion, pure erosion, and erosion–corrosion in NaCl solutions with variable pH values. The schematic illustration is shown in Fig. 7 respectively. The addition of sand to a NaCl solution with a pH of 3 caused a transition in the corrosion behaviour from widespread corrosion to localised pitting damage. The change was caused by the shift of the primary cathodic reaction from hydrogen evolution to oxygen reduction, resulting in a detrimental combined effect on overall erosion–enhanced corrosion. Nevertheless, the occurrence of pitting damage under these circumstances may lead to intensified erosion–corrosion, hence potentially exacerbating erosion specifically in the areas affected by pitting. Under conditions of active corrosion (pH 7–11), an increase in pH resulted in more extensive pitting damage. This was caused by the concentration of initial anodic sites and the hindered movement of the electrolyte. The presence of non-uniform

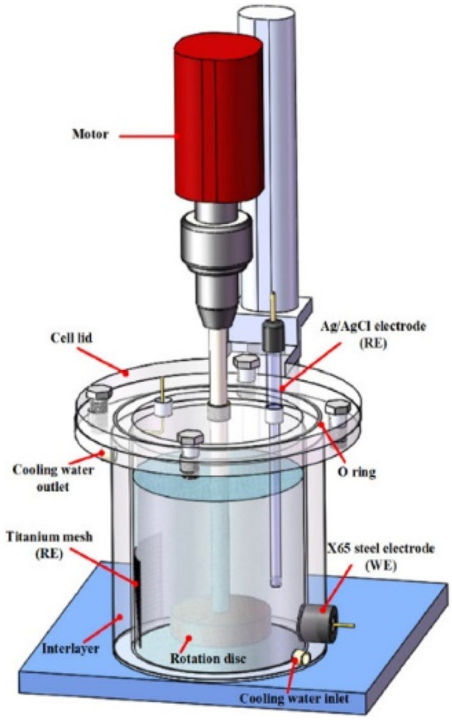


Fig. 7 Schematic diagram of the rotation disc system for investigating the carbon-steel under different types of erosion [40]

corrosion at these pH values may result in imprecise evaluations of the interaction between erosion and corrosion when employing conventional electrochemical and gravimetric measures. X65 carbon steel achieved passivation when exposed to a pH of 13. The presence of sand under these conditions resulted in the deterioration of the protective layer and the creation of unstable cavities. Although the passive layer could regenerate rapidly, its occasional deterioration and the resulting increase in surface roughness contribute to a decline in resistance against pitting corrosion. This, in turn, may lead to an overall acceleration of the corrosion process, particularly when fluid velocities are high.

2.28 Water Jet Erosion Performance of Carbon Fibre and Glass Fibre Reinforced Polymers: August 2021 [41]

Jesus Cornelio Mendoza and his team investigated on the leading-edge erosion of wind turbines through water jet erosive wear tests on carbon fibre-reinforced polymers (CFRP) and glass fibre reinforced polymers (GFRP). They used vacuum infusion process (VIP) to obtain composite materials using bidirectional carbon and glass fabrics for manufacturing the plates. To focus on the leading-edge erosion, a water jet injection platform was used to project liquid onto the specimen surface for high-pressure simulation purposes. The specimens are subjected to erosion with different durations and impact angles. SEM, optical microscopy, and a 3D optical profilometer play an important role in the investigation of the quantity of damage on surfaces, roughness determination, and scar profile analysis. The result shows that the volume reduction for uncoated carbon fibre is roughly double that of uncoated glass fibre, at 19 against 10 mm^3. The authors concluded that uncoated glass fibre has lower erosion resistance compared to uncoated carbon fibre, but both composite materials play a crucial role in erosion prevention.

2.29 Erosion Mapping of Through-Thickness Toughened Powder Epoxy Gradient Glass-Fibre-Reinforced Polymer (GFRP) Plates for Tidal Turbine Blades: February 2021 [42]

The literature review by Emadelddin Hassan and the team was based on a tidal turbine blade. The authors revealed that there are several factors that influence the erosion rate, including the velocity, angle of impact, and nature (i.e. size, shape, and hardness) of the eroding particles. Besides, environmental factors such as the presence of moisture, temperature, and chemical exposure are also major challenges that influence the erosion of coating materials. The studies revealed that GFRP showed a unique set of erosion behaviours influenced by factors including fibre orientation, matrix composition, and external environmental conditions. The erosion resistance of these materials is critical to determining the lifespan and efficiency of the tidal turbine blade. The experiment conducted provided an analysis of the gradient-toughened GFRP composites. An epoxy manufacturing system was used to make GFRP, which is made up of glass-fabric-reinforced laminates with different levels of epoxy matrix toughness. The erosion test was simulated in a marine environment where it mimics the conditions of a tidal turbine blade in actual working principle. The authors revealed a significant finding where the impingement angle was placed at 15°; it illustrates the minimum loss, and with a higher impingement angle, the gradient-toughened plates exhibited superior performance compared to standard epoxy plates, especially at angles of 0° and 45°. Moreover, in terms of ductility and erosion resistance, it demonstrated a more ductile response to erosion. The author noticed that the peak mass loss occurred at an impact angle of 60°, compared to 90°. The author suggested that gradient-toughening should maintain mechanical properties including tensile, comprehensive, and flexural strength.

2.30 A Review on Corrosion, Mechanical, and Electrical Properties of Glass Fibre-Reinforced Epoxy Composites for High-Voltage Insulator Core Rod Applications: Challenges and Recommendations: August 2021 [43]

Ogbonna and co-partners conducted a study on the development and application of glass fibre-reinforced epoxy composites in high-voltage insulator core rods. The authors mentioned that glass-fibre-reinforced-epoxy composites are commonly used as materials for fabricating core rods in high-voltage transmission lines. These materials have the major weakness of poor interfacial bonding, brittle fracture, stress corrosion cracking, water absorption and decay-like fracture. Therefore, the review aimed to discuss the impact of glass fibres on the corrosion, mechanical and electrical properties using E-glass and electrical corrosion resistance glass fibre combined with epoxy. Research has indicated that the presence of moisture causes glass/polymer composites to have a higher dielectric constant. The electrical characteristics of ECR-glass-reinforced epoxy composites during water exposure were investigated. A relationship between moisture absorption and leakage currents in fibreglass-reinforced epoxy matrix composites was observed as low-seed ECR-glass fibre composites exhibited lower leakage currents than high-seed ECR-glass composites. The authors reveal that there were good enhancements to epoxy composites for composite core rods using boron-free glass (ECR-glass) for reinforcement. In stress corrosion cracking (SCC) scenarios, ECR-glass-reinforced epoxy composites surpassed E-glass-reinforced composites. Compared to E-glass fibres, ECR-glass fibres showed better resistance to SCC. Because of its stronger electric field and the presence of metallic ionic numbers such as $Zn2+$ and $Ti4+$, which impede ion transport and limit migration potential, ECR-glass showed superior acid resistance than E-glass. In addition, it was noted that the network hydrolysis of ECR-glass in corrosive media happens far less quickly, suggesting that the reaction product of hydroxyl groups on the surface of the glass fibre does not weaken the fibre. Mechanical properties of ECR composites were found to decrease with time due to matrix decomposition and interface problems. It was discovered that E-glass-reinforced epoxy composites had stronger synergistic effects than ECR-glass-reinforced epoxy composites. For composite insulator core rods on outdoor transmission lines, ECR-glass fibre/epoxy composites and E-glass fibre/epoxy composites were considered effective. However, the authors concluded that problems with compliance during manufacture must be resolved as future works.

2.31 Review of Manufacturing Process of Natural Fibre Reinforced Polymer Composites: 30 April 2021 [44]

The review paper discusses several manufacturing processes for natural fibre reinforced polymer composites (NFRCs) and their impact on the mechanical properties of the final products. Azman and the researchers used inspection compression moulding process for injecting molten resin into a mould and then shaping it under compression. It ensures uniform resin distribution and high surface detail, resulting in durable products. However, it has lower tensile strength than most thermosets and requires careful control of temperature and pressure. Then, pultrusion process was used, and it is a continuous process that forms materials with a consistent cross-section. It is used for high-performance products in aircraft, aerospace, and corrosion resistance parts. While it produces high-strength parts, the method has drawbacks such as fragility, environmental concerns, and limitations due to high viscosity of thermoplastics. After that, resin transfer moulding (RTM) was used to preform stacks or dry woven s are placed in a mould, and a resin mixture is injected. This method is known for good surface finishing, low void content, and low tooling costs. RTM faces challenges such as mould design limitations and potential air leaks. Furthermore, the author used sheet moulding compound which is a fibreglass-reinforced thermosetting compound used in various industries. It offers good mechanical properties, is environmentally friendly, and allows for complex shapes. However, it faces issues such as continuous thickening of the paste and limitations in volume and continuity. Moreover, compression moulding, a high-volume, high-pressure method is ideal for automotive parts. It is suitable for large products and high-priced materials with minimal waste. The process requires precise control of viscosity, polymer matrix sheets, heat, and pressure. Its limitations include difficult material flow in the cavity, long processing times, and challenges with the microstructure of the -resin matrix. The result showed that compared to the tensile and flexural properties, resin transfer moulding exhibits higher tensile strength (i.e. 1621 MPa) than compression moulding (i.e. 1347 MPa). In terms of flexural strength, resin transfer moulding also exceeds compression moulding with 2276 MPa against 2247 MPa, respectively. However, the impact resistance strength of polymer composites made from resin transfer moulding is lower than that from the compression moulding process.

2.32 Physical, Mechanical, and Thermal Properties of Natural Fibre-Reinforced Epoxy Composites for Construction and Automotive Applications: 20 April 2023 [45]

This comprehensive review examines the potential of natural-reinforced epoxy composites (NFRCs) for various engineering applications, focussing on their physical, mechanical, and thermal characteristics. Epoxy, known for its excellent mechanical properties and versatility, has emerged as the preferred matrix material for NFRCs. By comparing NFRCs with synthetic composites, researchers highlight the eco-friendliness and sustainability of NFRCs. The corrosion resistance and eco-friendliness of epoxy based NFRCs, combined with natural fibres, make them ideal materials for structural and automotive applications. In addition, they noted that when depolymerised natural rubber was grafted with 1 wt.% of methyl methacrylate/glycidyl methacrylate, it exhibited an impact strength of 163% higher than that of epoxy resin. An investigation of the impact of loading on the tensile and flexural strength of wood dust-reinforced epoxy composites. The composites containing 10 wt.% of fibres had superior mechanical properties, with a 161% enhancement in tensile strength and a 200% improvement in flexural strength. The use of a 1% NaOH solution resulted in a 52% increase in tensile strength and a 16.65% increase in flexural strength. The NFRCs underwent thermal ageing at a constant temperature of 90 °C for durations of 7, 15, and 30 days. With an increase in the duration of thermal ageing, the scratch resistance of the composites exhibited a decline. The study utilised natural fibres of lengths measuring 10, 20, and 30 mm. It was observed that the hardness of the composites reduced as the length increased up to 20 mm. The authors claimed that the decrease in hardness is attributed to the occurrence of voids during the fabrication process.

2.33 Mechanical and Erosion Characteristics of Natural Fibre Reinforced Polymer Composite: Effect of Filler Size: 9 October 2019 [46]

The objective of this work is to create needle-punched non-woven composites that are strengthened with natural jute fibres specifically for use in automobiles. Reinforced polymer (FRP) composites in the automobile sector often utilise a range of natural fibres such as jute, kenaf, hemp, banana, and sisal. These fibres are chosen for their lightweight properties, environmentally favourable characteristics, widespread availability, and cost-effectiveness. The main aim of this study is to examine the erosion characteristics of these FRP composites, specifically in dusty conditions. To accomplish this, the researchers utilised the vacuum assisted resin transfer moulding (VARTM) technique to fabricate the composites. The filler size of the composite materials was altered, specifically employing three sizes: 10, 25, and 50. The composite specimens comprised four layers of needle-punched jutes, each measuring 250×250 mm, with the inclusion of mill scale at a % ratio of epoxy. The composite sample C1, with a filler size of, demonstrated the maximum tensile strength of 45.564 ± 0.72 MPa and flexural strength of 73.16 ± 1.34 MPa. The erosion rate of sample C1, with a filler size of 10, was dramatically reduced to 216.67 mg/kg when exposed to a 30° impingement angle, in comparison to sample C2 (25) and C3 (50). The mechanical characteristics and erosion performance of these composites were evaluated under varying situations. The use of sample C1 with a filler size of 10 exhibited exceptional mechanical strength and erosion resistance, indicating its potential suitability for automotive applications in dusty situations.

3 Review Works on Design of Wind Turbines/Cooling Towers

3.1 Experimental Study on the Design of a Cooling tower for a Central Air-conditioning Plant: March 2014 [47]

The research conducted by P. Balashanmugam and G. Balasubramanian provides a comprehensive study on the design, components, methodology, and various aspects of cooling towers, particularly in the context of a central air-conditioning plant. The authors mentioned that the important components of cooling towers are detailed, including frame and casing, fill material, cold water basin, drift eliminators, air inlet, louvres, nozzles, and fans. The performance of cooling towers is evaluated based on parameters which is the difference between inlet and outlet water temperature, approach, the difference between outlet water temperature and ambient wet bulb temperature, cooling capacity, evaporation loss, and cycles of concentration. Through the experimental study, the authors found various factors influencing cooling tower performance, such as capacity, range, heat load, dry and wet bulb temperatures, and ambient air humidity. The result highlights key design factors such as maximising air–water contact, facilitating air flow, minimising water loss, considering water quality issues (like corrosion and fouling), and spatial and noise considerations. The above is summarised in Fig. 8 respectively.

3.2 Basic Calculations involving Cooling Towers: July 2021 [48]

Jurandir Primo illustrated the design of cooling towers involves several critical components. Most towers have structural frames that support the exterior casings, motors, fans, and other components [49]. In some smaller designs, the casing itself may serve as the frame. The author used two types of fills which are splash fill and film fill. Splash fills occurs when water falls over horizontally over the splash bars, breaking into smaller droplets and wetting the fill surface. Plastic splash fill is more efficient than wood splash fill.

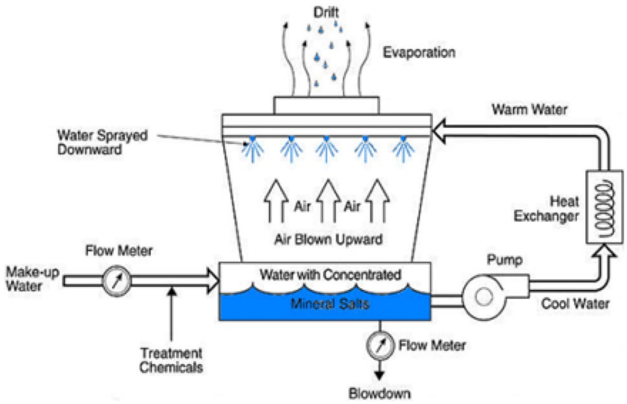


Fig. 8 Experimental study on the design of a cooling tower [47]

On the other hand, film fill consists of thin, closely spaced plastic surfaces over which water forms a thin film which is in contact with air. Film fill is more efficient than splash fill, providing the same heat transfer in a smaller volume. The components used included cold water basin, drift eliminators, air inlet, louvres, nozzles, and fans. A schematic illustration on crossflow and counterflow design of cooling towers is shown in Fig. 9 respectively.

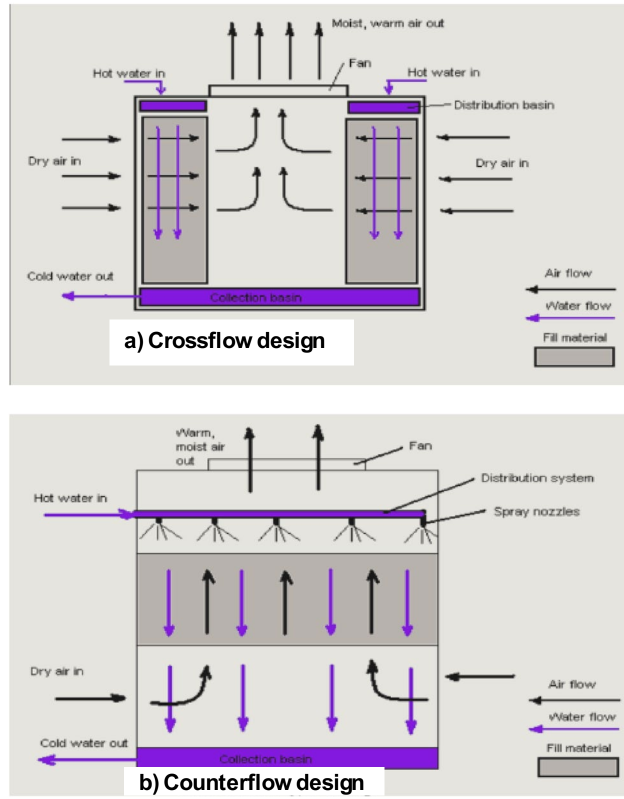


Fig. 9 Types of flow design in cooling towers [49]

3.3 Design and Fabrication of Mini Cooling Tower: April 2020 [50]

The study conducted by A. Bhatia used frame and base to provide structural support for the tower, while the louvres help in equalising air flow into the fill and retaining water within the tower. The storage tank collects and stores cooled water, exhaust system to facilitate the exit of air from the tower, fan to induced airflow through the tower, pipe network distributes water throughout the tower, pump to circulates water within the tower and honeycomb structure to serve as an interface between water and air to enhance the heat transfer. The overall design is shown in Fig. 10 respectively. The author claimed that the cooling tower occupies less space as compared to the conventional gigantic cooling towers.

3.4 Pilot-Scale Cooling Tower to Evaluate Corrosion, Scaling, and Biofouling Control Strategies for Cooling System Makeup Water: February 2012 [52]

S. H. Chien and the researchers designed a pilot-scale cooling tower which involves the integration of various systems and components to effectively study corrosion, scaling, and biofouling control strategies, especially when using alternative water sources like treated municipal wastewater. The element shown in Fig. 11 includes a counterflow evaporative cooling system which ensures efficient heat transfer and cooling. Besides, it uses a heating system to generate a consistent heat load for testing and evaluation. Then, the monitoring system used by the author functions for corrosion, scaling, and biofouling to assess the impact of different water qualities and treatment strategies. Furthermore,

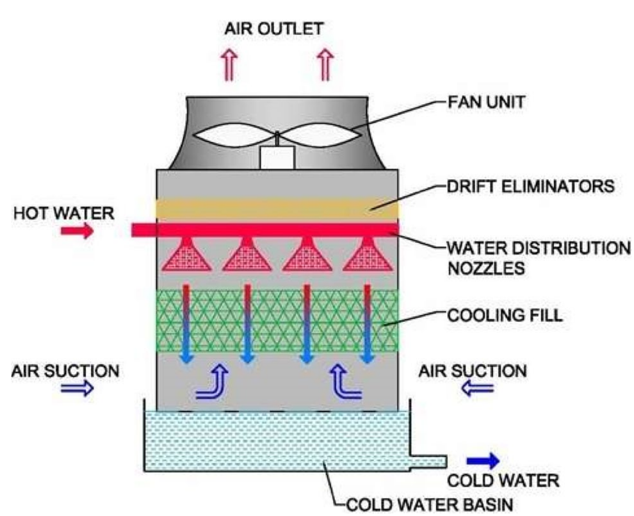


Fig. 10 Induced draft of a cooling tower [51]

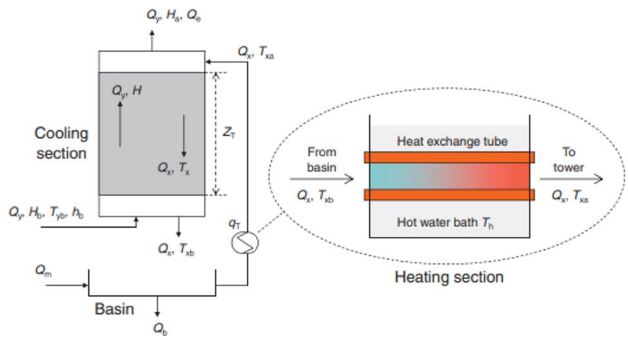


Fig. 11 Flow diagram of a cooling tower with a counterflow cooling system and a heating section for corrosion inspections [52]

the makeup water control system was used to manage the introduction of new water into the system. Moreover, they used blowdown control systems to regulate the concentration of minerals and impurities. Lastly, the power control system managed the energy input and operational parameters of the tower.

3.5 Design Methodology of Small Cooling Tower: March 2019 [53]

S. Jothibasu and co-partners showcased the configuration of a compact cooling tower shown in Fig. 12. The selection of fill material, drift eliminators, water distribution systems, fans, and motors for the small cooling tower would be dependent on specific performance requirements. The design procedure primarily entails conducting thermal and fluid dynamic calculations to guarantee effective heat transmission and adherence to pertinent norms and regulations. In addition, maintenance and operational factors would be considered to enhance the tower's efficiency and lifespan.

3.6 Efficacy of Cooling Towers: April 2015 [54]

The study examines the efficacy of cooling towers as shown in Fig. 13, by investigating the variables that impact their operational effectiveness. The study focussed on several essential components, namely frame and casing, fill, cold water basin, drift eliminators, air inlets, louvres, nozzles, and fans. The study also examines cooling tower performance parameters such as cooling capacity, evaporation loss, cycles of concentration, and liquid-to-gas ratio.

3.7 Design and Fabrication of an Improved Mini Cooling Tower for Nigeria Industries: May 2015 [55]

Adeyemi and co-partners design and fabricated an improved mini cooling tower (IMCT) that effectively solves the

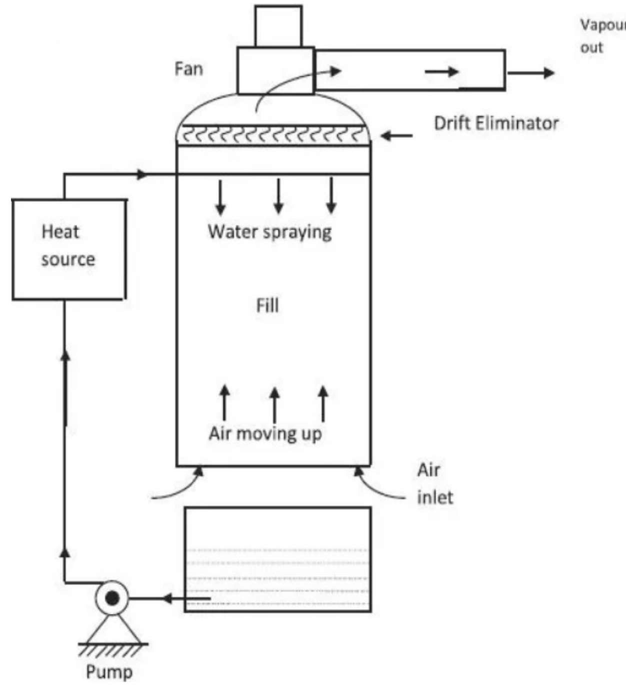


Fig. 12 Schematic diagram of a simple cooling tower [53]

problems encountered when maintaining conventional cooling towers in Nigeria. The schematic diagram of their design is shown in Fig. 14. They showcased that by substituting the drift eliminator with a specifically engineered condenser fin and utilising materials such as galvanised steel and Aluminium Alloy AA 1100, the IMCT not only improves thermal efficiency but also provides a cost-efficient and easy-to-maintain. This innovation is especially advantageous for companies and laboratories in need of efficient and cost-effective cooling solutions. They revealed that the outcome of their IMTC showed a reduction of temperature by an average of 24 °C. The overall heat transfer coefficient was 2298.85 W/m^2.°C, which was attributed to the fins material which they claimed to have a good thermal performance in heat dissipation during the cooling process.

3.8 Crucial Parts and Components of a Cooling Tower: May 2017 [57]

The cooling towers consist of multiple crucial components that are necessary for their efficient functioning and extended lifespan. The components encompass gearboxes, which exhibit diverse designs and reduction rates; fill media, essential for optimising water evaporation; drift reducers, which recycle moisture; nozzles, specifically employed in crossflow towers; and fans, indispensable for facilitating air circulation in mechanical draft towers. In addition, driveshafts transmit energy to facilitate the rotation of fan blades. Air intake louvres serve the purpose of preventing

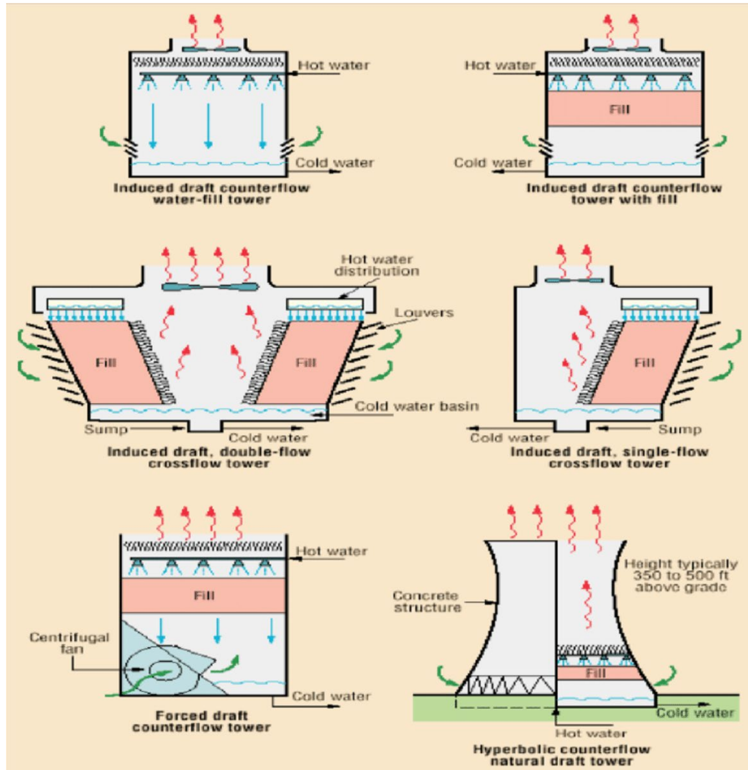


Fig. 13 Schematic diagram on factors governing the efficiency of cooling towers [54]

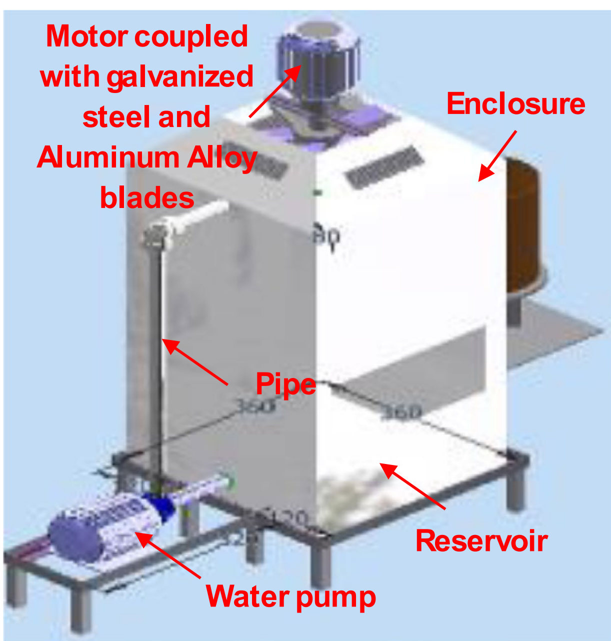


Fig. 14 Cooling tower interior design [56]

contamination and regulating water usage. Electric float valves are responsible for ensuring proper working with minimal maintenance requirements. Lastly, reservoir heaters are employed to prevent water from freezing in colder areas. Every individual component has a distinct function in ensuring the efficiency and longevity of cooling towers in different scenarios. Figure 15 shown the schematic diagram of a basic cooling tower. It is to be reminded here that, it is based on this basic setup that there is huge research paid on cooling towers namely focussing on the efficiency and the effectiveness of it subjected to a given application.

3.9 Mechanical Draft Counterflow Tower: November 2010 [59]

Chris Haslego's research demonstrated the design of cooling towers necessitates meticulous attention to both structural and operational components to guarantee optimal efficiency and long-lasting durability. The chosen materials usually consist of metals that are resistant to corrosion and durable polymers, specifically selected for their capacity to endure prolonged contact with water and fluctuating temperatures. The design process is guided by the concepts of thermodynamics and fluid dynamics, with a focus on optimising heat transfer efficiency while minimising water and energy use. Engineers utilise advanced modelling tools to forecast and enhance the efficiency of the cooling tower across different operational scenarios. The combination of material science and engineering principles is crucial for the development of efficient and environmentally friendly cooling tower systems. Figure 16 shows the schematic diagram of Chris Haslego's research.

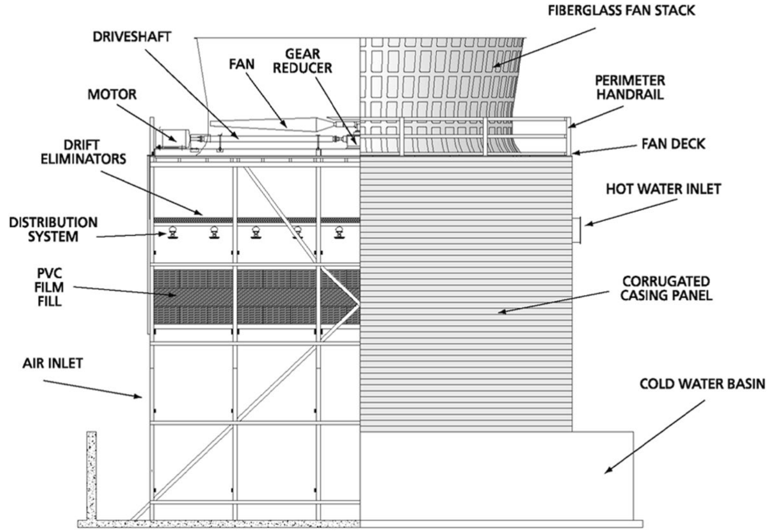


Fig. 15 Basic components of a cooling tower [58]

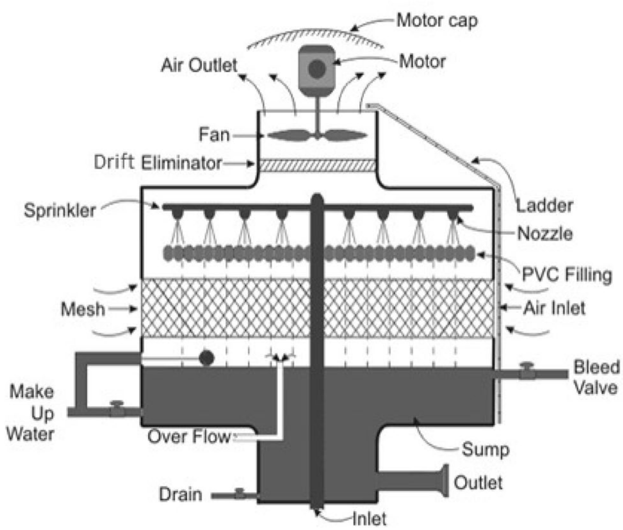


Fig. 16 Mechanical draft counterflow tower [60]

3.10 Advancement of Cooling Tower Materials: April 2021 [61]

Cooling towers, which are essential components of HVAC systems, have undergone advancements in both their design and the materials used. Conventional metal towers, constructed from galvanised or stainless steel, provide long-lasting performance but encounter difficulties such as corrosion, scaling, and maintenance requirements. Besides, contemporary HDPE (high-density polyethylene) cooling towers offer numerous benefits. These materials exhibit chemical resistance, are lightweight yet strong, and contain antibacterial resins to inhibit bacterial development. In addition, HDPE towers provide easy installation, economic efficiency, and extended warranty periods. The selection between metal and HDPE hinges upon the specific requirements of the building and the guidance of professionals, with the inclusion of materials such as fibreglass being considered in certain situations.

4 Review Works on Erosion-Resistant Coating Material

4.1 Zirconia Nanoparticle Coating for High-Strength and Alkali-Resistant Glass Fibres: November 2023 [62]

The team investigated on the chemical and mechanical properties of E-glass fibre for use in an alkaline environment with the impact of zirconia nanoparticle coating. Alkali-free glass fibres were dip-coated in aqueous solutions containing varying quantities of zirconia nanoparticles. Then, the authors performed a tensile test on both uncoated and coated fibres to evaluate the impact of nanoparticles on fibre strength. The alkali resistance was tested in a NaOH alkaline solution; thus, it can evaluate the corrosion resistance and mechanical properties of aged fibres after dwelling in an alkaline environment. The mechanical properties of coated fibres displayed tensile strengths that improved by 10.2, 12.2, 14.6, and 17.4% when coated fibres were dissolved in solutions containing 5, 10, 15, and 20% nanoparticles, respectively. In other words, zirconia coating showed a positive effect on the E-glass fibre mechanical properties. Besides, it showed a greater alkali resistance of Zirconia nanoparticle-coated fibres with 15 and 20% solutions to corrosion in a NaOH-based alkaline environment. The coating kept the mechanical properties from weakening, and the tensile capabilities of aged fibres remained consistent. The study reveals that in an alkaline environment, zirconia nanoparticle coating effectively prevents corrosion and increases the tensile strength of E-glass fibres.

4.2 Usage of Fibre-Glass Materials for Protection of Industrial Pipes Against Corrosion: December 2019 [63]

P. Venhrynyuk and V. Popovich developed a novel method based on fibreglass materials as a coating to enhance the resistance of pipelines to cracks and corrosion defects. They claimed that this coating plays a crucial role in protecting the pipeline with characteristics such as heat resistance, strength, high adhesions to steel pipes, insulation, and anti-corrosion properties. The coating demonstrates strong resistance to heat and durability under a range of operational circumstances. The inclusion of a fibreglass layer improves the coating's wetting and adherence to epoxy resins, as well as its static and dynamic strength. Besides, the low shrinkage of epoxy resins during hardening can prevent the formation of microcracks on the coating surface. Between the heated polyurethane coating and fibreglass, an elastic layer was ensuring consistency, performance, and suitability for the cathodic protection system. Furthermore, the coating can be used in both underwater and dry surroundings while displaying a resilience in wet surroundings and dry surroundings at temperatures up to 65 and 100 °C, respectively. The coating is mainly designed for oil and gas pipelines since it can find applications in various industries for protecting pipelines against corrosion and mechanical damage. This innovative coating contributed to the longevity and integrity of critical infrastructure in diverse environments.

4.3 Epoxy-Based PANI/zinc Oxide/Glass Fibre Nanocomposite Coating for Corrosion Protection Of Carbon Steel: September 2017 [64]

This research provides an innovative and practical approach using nanocomposite coatings, which is a significant improvement in the field of corrosion prevention for carbon steel in the engineering industry. Rouhollah et al. showed that the conductivity and durability of PANI makes it an excellent candidate for protecting against corrosion. The development of phosphate–metal complexes on the metal surface shows that the addition of dodecyl benzenesulfonic and phosphoric acids as particles enhances PANI's corrosion shielding efficacy in addition to increasing its solubility in organic solvents. Moreover, the authors had mentioned that adding zinc oxide nanoparticles can increase corrosion resistance even more by changing steel's corrosion potential to a more positive potential. For further enhancement, the polymerised PANI mixture, epoxy resin, and E-glass fibres are combined to create a coating that improves impact resistance by increasing flexibility. The research showcased that the PANI/zinc oxide/glass fibre composite greatly enhances coating properties when the weight-to-weight percentage is optimised. The coating was then tested by DC polarisation tests and stress strain analysis to evaluate the coating efficacy. The authors further claimed that observations through scanning electron microscopy showed that the durability of the nanocomposite improved after tests. This was evidenced by the SEM images where the material blend formed an excellent bond with minimum or no pores within the matrix.

5 Future Research

From the review done, it is noticed that there is not any specific coating material that demonstrates an optimum wear to the fan blades of a cooling tower/wing turbine subjected to LEP. Although, scientists and researchers worldwide agree that diamond is the hardest substance in the earth contributing to many advantages, the sole and discrete factor that they are not generally preferred is due to their high cost. The closes one may achieve is to use them in LEP as a coating substance which can withstand high erosion rate as compared to cast iron material which is heavily used in LECT/WT. This is where numerous works has been reported in the literature on the race to find a cost-effective coating material for the use in LECT/WT. With regard to this, the following below but not limited to are the possible future works that could open new research pathways on the afore said topic. They are listed as follows:

- Umar and co-workers had reported in Ref. [65] that there is a significant interest on natural fibres as compared to synthetic fibres like glass fibres in the tribological field of study. Hence, different types of fibres may be explored ad a potential reinforcement to polymers matrix in the application of LEP specifically on erosion wear on cooling turbine blades. These fibres include betelnut, oil palm, jute, kenaf, sugarcane, date, banana, pineapple and other natural fibres.
- Belal and co-workers had reported in Ref. [66] that fibre layout in the matrix plays a crucial role in determining the overall strength of the matrix (i.e. tensile, compression, bending and impact strength of the matrix). Hence, it is a great attention to pay on different fibres in the polymer matrix for the use in LEP of turbine blades in cooling towers and wind turbines.
- Nirmal and co-workers had revealed in their work in Ref. [67] that it is crucial to treat natural fibres with appropriate chemical treatment prior to their usage as reinforcements in the matrix. This is because, natural fibres are hydrophilic in nature and tends to absorb water over

use of time which can degrade the overall performance strength of the composite in various applications. Having said that, one may explore on the potential of various natural fibres on modifying it fibre properties to being more 'hydrophobic' to the subjected application. In this case would be in the use of LEP of turbine blades used in cooling towers and wind turbines.

- It is well known in the literature that surface wettability of natural fibres has a great influence of the composite's overall strength, i.e. too many fibres will worsen the surface wettability of the composite and a ductile like behaviour is likely to occur. This will cause the composite to fracture under loading conditions [68, 69]. Hence, Nirmal and co-workers had investigated in Ref. [70] that it is crucial to treat the fibres with different types of alkaline treatment and to observe the interfacial shear strength of individual fibres in the matrix. Here, two crucial observations can be made namely on the optimum treatment to the natural fibre that leads to the maximum interfacial shear strength of the fibre/resin before fibre failure occurs. Second, the critical embedded length of the fibre in the resin which results in the maximum pullout force, i.e. highest surface wettability. Knowing these two parameters, will result in an effective way of material selection in particular natural fibre composites in the use of LEP of cooling fan blades in a cooling tower and wind turbine.
- In year 2010, a study was conducted by the participating authors on the effect of fibres treatment and contact conditions on adhesive wear and frictional performance of polyester composites [71]. In short, the layout of fibres plays a crucial factor in composite fabrication which will yield to an optimum wear in given conditions. In the case of LEP applications, the layout of fibres in the matrix may not only improve erosion wear but also influence on the aerodynamic properties of the fan blades of the cooling towers and wind turbines.
- The feasibility of using rubberised elements in coating materials in LEP to the turbine blades used in cooling towers has been lacking in the science of literature. Rubber has demonstrated its natural capabilities to withstand erosion wear as it does not contain 'iron' substances within the chemical structure of it. For an instance, Sanjeev and co-workers in Ref. [72] had proven that rubcrete composites which are made up from rubber particles reinforced concrete has a future in the construction industry. Further to this, one may explore the suitability of mixing different rubber mesh of different sizes in liquid polymer or cement to achieve an effective coating to LEP of cooling fans used in cooling towers and wind turbines.
- There are also cases where synthetic glass fibre namely in chopped strand mat (CSM) is preferred to me used as a coating element as a LEP to turbine blades. However, due to their weight to ratio of the polymer, it may cause a burden on the turbine blades and hence effecting the overall efficiency of the cooling tower. But its worthy to try them in different form such as glass particulate or fine granule in the matrix as a low weight coating material to the latter. Umar and co-workers had proven that glass fibres are almost competitive in their tribological applications in [73].
- Back in year 2009, Umar and Belal discovered a unique character of betelnut fibres [74]. The fibre outer surfaces had tiny hairy spots termed 'trichomes' which had never been evidenced on other natural fibres. This 'trichomes' had the ability to lock the betelnut fibre in the resin well thereby preventing fibre pullout during dry and wet adhesive sliding subjected to a rotating stainless-steel counter face. With this knowledge, one may explore the possibility of using betelnut fibres reinforced polymer composite as a coating element to turbine blades used in cooling towers and wind turbines on the LEP characteristics.
- Powder coating is also another approach that serves excellent erosion resistant to the base metal; i.e. cast iron [75]. The working principle is that the base metal which is to be powder coated must electrostatically charge and be heated to a certain temperature. Following to this, fine pigmented resin which are electrostatically charged is sprayed to the based material. The challenge is that the base material must be free from any impurities before this application. Although powder coating technology had been commonly used by the LEP industry, they offer some disadvantages such as being susceptible to chipping and scratching over long period of use [76]. Second, the curing process involves temperatures above 200 °C, which can lead to potential damage of the base metal if its exposed too long. On the other hand, powder coating surfaces are rough by nature; i.e. evident of irregular pores which is due to the pigmentation of the powder during the spraying process. In this regard, they offer less attention as a coating material to the wind turbine blades of a cooling tower/wind turbine; i.e. high drag force exerted to the blades due to the uneven surface which will cause unwanted vibration and sound during usage [42]. It is, therefore, proposed that the methodology of powder coating technology to be further researched. This could be on the research on smooth surface looks of the coating element with enhanced surface adhesion against the latter preventing chipping of the coating and surface cracks.

6 Summary of Reviewed Works

After conducting the literature review from previous published works, a few points are worthy to be noted. They are as follows:

- The evolution on LECT/WT of a wind turbine/cooling towers shows a significant research interest where there has not been any definite solution for an optimum wear resistance on the latter.
- Natural and glass fibre concrete was still a notable shortfall in the search for a substance that efficiently combines affordability, durability, and environmental footprint. Due to this gap, natural and glass fibre concrete were investigated as possible substitutes. These materials were chosen for their ability to provide a sustainable and cost-effective solution while maintaining or improving the durability and erosion resistance of the cooling tower and wind turbine components.
- This review further showcased that the advantages of natural fibre-reinforced concrete offer a new opportunity for sustainable development in industrial applications due to its environmentally friendly nature. The combination of its resistance to erosive pressure and its commitment to the environment makes it an extremely attractive candidate to LECT/WT. Glass fibre-reinforced concrete is known for its high strength-to-weight ratio and it is a durable material that can withstand the demanding conditions of cooling towers. It helps to extend the blade life and ensure efficient operation subjected to LECT/WT.
- On the other hand, materials such as ceramics, epoxy or polyester resin composites and other metallic coatings, are also well known for their special properties such as corrosion resistance, durability, and ability to extend the lifespan of a given component used particularly in cooling towers and wind turbines.
- The review emphasised that carbon steel, the traditional material used for cooling towers, is commonly susceptible to erosion during normal operations. This has led to the investigation of different coating options. Researchers showed that different coating materials subjected to cast iron used in cooling towers and wind turbines had contributed to a longer lifespan of the latter.
- Review works further showcased that the design of cooling towers and wind turbines is not a limitation as it can be customised to suit different geographical regions throughout the world namely to cater the high efficiency of the cooling towers and wind turbines.
- There has been a clear tendency to prioritise high-end solutions such as diamond coating. Although diamond coating has excellent erosion resistance due to its unrivalled hardness and high melting temperature, it is not a realistic choice for large industrial applications due to its excessive cost. The emphasis on high-quality solutions distracted from the investigation of more economical and equally feasible options.
- The authors of the current work found out that to solve LECT/WT, the investigation of natural and glass-fibre-reinforced concrete represents a significant shift in the way we approach the problem of LECT/WT and aims to provide a more efficient solution. These materials provide the essential physical properties to effectively resist erosion, while being in way with the increasing industry focus on sustainability and cost efficiency. This method addresses the imbalance in the industry by moving away from overly costly solutions to more viable and environmentally friendly alternatives.
- Lastly, this review highlights a shift in the industry towards the use of innovative and sustainable materials such as natural and glass-fibre-reinforced concrete. This transition is driven by a desire to find a balance between cost, performance, and environmental sustainability, moving away from traditional materials and high-end solutions.

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Declarations

Competing interests The authors declare no competing interests.

Ethical Approval Not applicable.

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