

MUHANDISLIK

& IQTISODIYOT

ijtimoiy-iqtisodiy, innovatsion texnik,
fan va ta'limga oid ilmiy-amaliy jurnal

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- 05.01.00 – Axborot texnologiyalari, boshqaruv va kompyuter grafikasi
05.01.01 – Muhandislik geometriyasi va kompyuter grafikasi. Audio va video texnologiyalari
05.01.02 – Tizimli tahlil, boshqaruv va axborotni qayta ishlash
05.01.03 – Informatikaning nazariy asoslari
05.01.04 – Hisoblash mashinalari, majmualari va kompyuter tarmoqlarining matematik va dasturiy ta'minoti
05.01.05 – Axborotlarni himoyalash usullari va tizimlari. Axborot xavfsizligi
05.01.06 – Hisoblash texnikasi va boshqaruv tizimlarining elementlari va qurilmalari
05.01.07 – Matematik modellashtirish
05.01.11 – Raqamli texnologiyalar va sun'iy intellekt
05.02.00 – Mashinasozlik va mashinashunoslik
05.02.08 – Yer usti majmualari va uchish apparatlari
05.03.02 – Metrologiya va metrologiya ta'minoti
05.04.01 – Telekommunikatsiya va kompyuter tizimlari, telekommunikatsiya tarmoqlari va qurilmalari. Axborotlarni taqsimlash
05.05.03 – Yorug'lik texnikasi. Maxsus yoritish texnologiyasi
05.05.05 – Issiqlik texnikasining nazariy asoslari
05.05.06 – Qayta tiklanadigan energiya turlari asosidagi energiya qurilmalari
05.06.01 – To'qimachilik va yengil sanoat ishlab chiqarishlari materialshunosligi
05.08.03 – Temir yo'l transportini ishlatish
05.08.06 – "G'ildirakli va gusenisali mashinalar va ularni ishlatish" (texnika fanlari)
05.09.01 – Qurilish konstruksiyalari, bino va inshootlar
05.09.04 – Suv ta'minoti. Kanalizatsiya. Suv havzalarini muhofazalovchi qurilish tizimlari
10.00.06 – Qiyosiy adabiyotshunoslik, chog'ishtirma tilshunoslik va tarjimashunoslik
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08.00.02 – Makroiqtisodiyot
08.00.03 – Sanoat iqtisodiyoti
08.00.04 – Qishloq xo'jaligi iqtisodiyoti
08.00.05 – Xizmat ko'rsatish tarmoqlari iqtisodiyoti
08.00.06 – Ekonometrika va statistika
08.00.07 – Moliya, pul muomalasi va kredit
08.00.08 – Buxgalteriya hisobi, iqtisodiy tahlil va audit
08.00.09 – Jahon iqtisodiyoti
08.00.10 – Demografiya. Mehnat iqtisodiyoti
08.00.11 – Marketing
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08.00.14 – Iqtisodiyotda axborot tizimlari va texnologiyalari
08.00.15 – Tadbirkorlik va kichik biznes iqtisodiyoti
08.00.16 – Raqamli iqtisodiyot va xalqaro raqamli integratsiya
08.00.17 – Turizm va mehmonxona faoliyati

Ma'lumot uchun, OAK
Rayosatining 2024-yil 28-avgustdagi 360/5-son qarori bilan "Dissertatsiyalar asosiy ilmiy natijalarini chop etishga tavsiya etilgan milliy ilmiy nashrlar ro'yxati"ga texnika va iqtisodiyot fanlari bo'yicha "Muhandislik va iqtisodiyot" jurnali ro'yxatga kiritilgan.

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SAND-PARTICLE-INDUCED LEADING-EDGE EROSION AND ITS IMPACT ON WIND TURBINE BLADES: A REVIEW

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Abstract: Surface erosion of wind turbine blades, particularly leading-edge erosion, is a complex multiphysical process strongly influenced by random environmental factors such as rainfall conditions, sand particle impacts, and coating defects, which can significantly reduce wind turbine efficiency. This study investigates the influence of sand particles on blade erosion through a review and analysis of most recent numerical and experimental articles. The results from numerical and experimental studies indicate that sand erosion can cause efficiency losses of over 44%, and demonstrate a significant reduction in wind turbine performance under sand erosion conditions.

Keywords: wind turbine blades, leading edge erosion, sand particle erosion, wind-blown sand, aerodynamic performance, blade degradation, desert environments, energy efficiency.

7Annotatsiya: Shamol turbinalari parraklarining sirt eroziyasi, ayniqsa, oldingi chekka eroziyasi, yog'ingarchilik sharoitlari, qum zarralari ta'siri va qoplama nuqsonlari kabi tasodifiy atrof-muhit omillari ta'sirida yuzaga keladigan murakkab multifizik jarayon bo'lib, shamol turbinasining samaradorligini sezilarli darajada pasaytirishi mumkin. Ushbu tadqiqot qum zarralarining shamol turbinasi parraklari eroziyasiga ta'sirini eng so'nggi raqamli va eksperimental maqolalarni ko'rib chiqish hamda tahlil qilish orqali o'rganadi. Raqamli va eksperimental tadqiqotlar natijalari shuni ko'rsatadiki, qum eroziyasi 44 % dan ortiq samaradorlik yo'qotishlariga olib kelishi mumkin va qum eroziyasi sharoitida shamol turbinasining ishlashi sezilarli darajada pasayadi.

Kalit so'zlar: shamol turbinasi parraklari, oldingi chekka eroziyasi, qum zarralari eroziyasi, shamol tarkibidagi qum, aerodinamik samaradorlik, parraklarning degradatsiyasi, cho'l muhitlari, energiya samaradorligi.

Аннотация: Поверхностная эрозия лопастей ветротурбин, особенно эрозия передней кромки, представляет собой сложный многофизический процесс, на который сильно влияют случайные факторы окружающей среды, такие как условия выпадения осадков, удары песчаных частиц и дефекты покрытия, что может значительно снизить эффективность ветротурбины. В данном исследовании изучается влияние песчаных частиц на эрозию лопастей на основе обзора и анализа последних численных и экспериментальных работ. Результаты численных и экспериментальных исследований показывают, что песчаная эрозия может привести к потерям эффективности более чем на 44% и демонстрирует значительное снижение производительности ветротурбины в условиях песчаной эрозии.

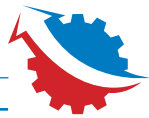
Ключевые слова: лопасти ветротурбин, эрозия передней кромки, эрозия песчаными частицами, песок, переносимый ветром, аэродинамические характеристики, деградация лопастей, пустынные условия, энергоэффективность.

INTRODUCTION

Global wind capacity now exceeds 1,346 gigawatts, and the amount of new capacity being added is increasing year by year. In particular, in 2025, more than 35% compared to 2024, or 169 gigawatts of energy generation capacity, was added [1]. This significant increase in onshore wind, offshore wind, and solar capacity has effectively reduced countries' coal imports by 700 million tonnes and natural gas imports by 400 billion cubic metres, resulting in estimated savings of USD 1.3 trillion since 2010 [2].

However, the maintenance of wind turbines remains an important cost factor, influencing the price of energy and the competitiveness of renewable energy [3]. For instance, onshore wind farm operators spent around USD 15 billion on operations and maintenance services in 2019, 57% of which was allocated to unplanned repairs [4]. The control system, gearbox, electrical system, generator, and hub and blades account for over 50% of all failures and 85% of the total downtime. Moreover, 90% of the costs of unscheduled replacements are attributable to these components [5].

The blades are one of the main components of a wind turbine. They act as a mechanism for capturing the



kinetic energy of the wind by converting aerodynamic forces into rotational motion, which is then transferred to the main shaft connected to a generator. These blades are manufactured from lightweight materials such as glass fibre or carbon fibre so that only a minimal amount of wind force is required to rotate them [6]. However, the efficiency of the blades decreases by up to 30% over their lifespan due to leading-edge erosion [7].

This review article aims to investigate the extent to which leading-edge erosion caused by sand affects the efficiency of wind turbine blades. However, the main factors contributing to leading-edge erosion include dust particles, UV radiation, hail, rain, temperature fluctuations, humidity, and other environmental factors [8]. This study specifically investigates and summarizes the extent to which sand particles reduce the energy efficiency of wind turbines.

REVIEW OF LITERATURE ON THE SUBJECT

The study conducted by Rotich and Kollár (2024) on the NACA 4412 airfoil investigated various surface roughness conditions and also examined how rime ice and glaze ice influence airfoil aerodynamic efficiency. The study clarified that aerodynamic performance with shallow roughness caused by sand erosion can result in optimal performance due to the trip effect, thereby increasing airfoil efficiency. Meanwhile, glaze ice causes greater performance degradation than rime ice because it forms non-uniform ice shapes [9].

Bouhelal et al. (2026) also studied the impact of windblown sand particles on the aerodynamic performance of wind turbine blades in desert environments under various sand particle sizes, concentrations, and interactions with wind turbine blades using a 3D Eulerian–Lagrangian computational model. The study showed that the performance of blades can be reduced by 2.8% due to small sand particles, while larger sand particles can reduce blade performance efficiency by 20%. The authors state that sand particles reduce aerodynamic efficiency by disrupting airflow and decreasing pressure, particularly at the blade's leading edge [10].

Zidane et al. (2020) used a numerical model of the NACA 63415 airfoil to investigate blade erosion rates under different sandstorm conditions. The study was conducted using a novel coupled application of a neural network, CFD, and BEM. The results showed that the power generated under debris flow conditions can decrease by 10–30% compared to clean conditions. Results based on the BEM method also showed that the power generated under sandstorm conditions can decrease by 30% compared to normal conditions [11].

The numerical studies conducted to investigate the impact of sand on wind turbine blades found that sand particles adversely affect blade performance. They can reduce blade efficiency by up to 30%, which is a significant reduction. The losses also depend on the size of the sand particles: the smaller the particle size, the lower the erosion rate.

Deshun Li et al. (2018) conducted an experimental study to evaluate the effects of wind velocity, particle diameter, and particle density on the erosion of wind turbine airfoils. They used the S809 airfoil in their study. By varying the angle of attack and Stokes number, they found that when the angle of attack (AOA) is 6.1° , no erosion occurs on the airfoil surface if the particle Stokes number is lower than 0.0135, whereas erosion occurs if the particle Stokes number is higher than 0.0151. This study revealed the relationship between the Stokes number and the angle of attack. The results indicate that blade erosion begins when the particle Stokes number exceeds 0.0151 [12].

Wan et al. (2024) conducted a case study to investigate blade performance after erosion. The experiment involved vehicle-mounted tests on scaled models of 1.5 MW wind turbine blades. They tested uneroded, leading-edge-eroded, semi-eroded, and fully eroded blades. During the experiment, the blade installation angles relative to the wind were set at 22.7° , 31.7° , 40.7° , and 49.7° . Different wind speeds were also considered. The results showed that, overall, the aerodynamic performance of the leading-edge-eroded blades was initially better than that of the uneroded blades. However, as erosion progressed and the blades became semi-eroded, their performance gradually decreased. Overall, the experimental results showed that the aerodynamic performance of wind turbine blades after initial erosion can be higher than that of blades without erosion [13].

Rezig et al. (2019) conducted a study on the NACA 4412 profile to determine the impact of sand on blade performance in arid areas. Tests were conducted using an erosion sandblaster and a wind tunnel on uncoated glass fibre/polyester blades at various impact angles and durations. The aerodynamic forces acting on a NACA 4412 profile were determined experimentally. All profiles (AR = 0.571) were tested in a wind tunnel at an air speed of 10 m/s and a Reynolds number of 6.5×10^5 . The results showed that the severe conditions of arid environments containing sand particles can reduce wind turbine efficiency by up to 45.44%. This means that energy production decreases significantly under such conditions, while blade durability is also reduced [14].

Muntenita et al. (2024) conducted an important experiment to investigate how blade material degradation occurs and evolves. They used samples from a commercial wind turbine blade made of a multilayer composite material. The samples consisted of an outer rigid polymer cover, two glass fibre fabric layers oriented at 45° , a

thick polymeric foam layer, and a base layer made of epoxy resin. These layers were bonded together to form the hybrid composite blade material. The results showed that the surface layer serves as the primary barrier protecting wind turbine blades from abrasive erosion. Once this protective layer is damaged, the underlying material deteriorates rapidly, which can ultimately lead to blade failure. The investigation of the main abrasive wear factors—particle velocity and exposure time—showed that particle velocity has approximately 20% greater influence than exposure time. The most important finding was that once the protective layer is eroded to a depth of approximately 0.6 mm, the degradation rate increases significantly. Continued exposure to abrasive particles accelerates material removal, eventually resulting in complete failure of the affected region. The erosion cavity then propagates through the material and reaches the underlying epoxy resin layer located about 11 mm beneath the outer protective surface [15].

Experimental studies show that sand erosion causes significant energy losses in wind turbines. The studies discussed above were designed to determine how sand erosion occurs, its critical limits, and the extent of energy losses under severe conditions. The findings indicate that the velocity and size of the sand particles impacting the blades are the most important factors affecting blade damage and can lead to an efficiency loss of more than 44%.

RESEARCH METHODOLOGY

The literature used in this study was obtained from the Google Scholar academic search engine. Particular attention was paid to selecting publications from recent years. In the literature review section, special emphasis was placed on articles published within the last five years, which were carefully selected and divided into two groups. The classification of the articles was based on their research methodology, where the studies were categorized into numerical (simulation-based) and experimental works. Initially, the numerical studies were analyzed, and the results related to the aerodynamic and efficiency performance of blades under sand impact were summarized and synthesized. Subsequently, the experimental studies were reviewed, and their findings were also summarized and synthesized.

ANALYSIS AND RESULTS

The reviewed studies indicate that sand erosion is one of the most influential environmental factors affecting the long-term aerodynamic performance and structural durability of wind turbine blades. Although numerical and experimental investigations consistently confirm that sand particles reduce blade efficiency, the magnitude of the reported losses varies according to the adopted methodology, environmental assumptions, and operating conditions. This comparison demonstrates that each research approach provides valuable insights while also presenting specific limitations.

The numerical studies generally focus on understanding the aerodynamic mechanisms through computational fluid dynamics (CFD), Eulerian–Lagrangian particle tracking, Blade Element Momentum (BEM) theory, and hybrid computational models incorporating artificial neural networks. These approaches enable researchers to evaluate the influence of particle diameter, wind velocity, particle concentration, and impact angle under carefully controlled conditions. Numerical simulations reported that aerodynamic efficiency losses typically range from approximately 2.8% under mild erosion conditions to nearly 30% during severe sandstorm events. These studies consistently demonstrate that erosion mainly affects the leading edge of the blade, where airflow first interacts with the airfoil surface. As the leading-edge geometry becomes rougher, the boundary layer separates earlier, reducing lift generation while simultaneously increasing drag. Consequently, the lift-to-drag ratio decreases, leading to lower power output and reduced energy conversion efficiency.

Despite these advantages, numerical investigations cannot completely reproduce the highly variable conditions encountered in natural desert environments. Wind speed, turbulence intensity, particle shape, moisture content, and continuously changing particle concentrations introduce uncertainties that are difficult to represent accurately within computational models. Most simulations assume steady-state operating conditions and simplified particle characteristics to reduce computational complexity. Although these assumptions improve computational efficiency and allow systematic parameter analysis, they may also underestimate the cumulative effects of long-term abrasive erosion observed during actual wind turbine operation.

Experimental investigations provide complementary evidence by examining blade performance under realistic erosion conditions. Wind tunnel experiments, erosion sandblasting tests, and vehicle-mounted field measurements demonstrate that aerodynamic degradation becomes increasingly significant as the protective surface layer deteriorates. Unlike numerical simulations, laboratory and field experiments capture the combined influence of environmental variability, material degradation, and complex particle interactions. The experimental



results therefore provide a more realistic estimation of blade deterioration over time.

One important observation reported in several experimental studies is that slight leading-edge roughness may initially improve aerodynamic performance due to the trip effect. Under certain operating conditions, a small amount of surface roughness promotes earlier boundary-layer transition from laminar to turbulent flow, delaying large-scale flow separation and temporarily improving lift characteristics. However, this beneficial effect is only temporary. As erosion progresses, the protective coating becomes thinner, exposing the underlying composite materials to continuous abrasive impacts. Once this protective layer is damaged beyond a critical depth, the erosion rate accelerates rapidly, causing severe material loss and substantial reductions in aerodynamic efficiency.

The reviewed literature also highlights the importance of sand particle characteristics. Larger particles possess greater kinetic energy during impact and therefore remove protective material more rapidly than smaller particles. Similarly, increasing particle velocity significantly increases erosion intensity because the impact energy rises proportionally with velocity. Experimental observations further suggest that particle velocity has a stronger influence on erosion than exposure duration. This finding explains why wind turbines operating in desert regions during frequent sandstorms experience considerably faster blade degradation than turbines installed in less abrasive environments.

A comparison of the reviewed studies indicates that the reported efficiency losses vary from approximately 2.8% under relatively mild erosion conditions to more than 45% in extremely harsh desert environments. Such variation reflects differences in experimental design, environmental severity, blade material properties, coating characteristics, and operating conditions rather than inconsistencies between studies. Overall, the findings consistently demonstrate that sand erosion gradually changes blade geometry, reduces aerodynamic efficiency, shortens component lifetime, and increases maintenance requirements.

Based on the collective evidence, both numerical and experimental investigations should be considered complementary rather than competing research approaches. Numerical simulations provide detailed understanding of aerodynamic behaviour and enable efficient evaluation of numerous operating scenarios, whereas experimental investigations validate computational predictions under realistic environmental conditions. Integrating these two approaches will improve the accuracy of future erosion prediction models, support the development of more erosion-resistant blade coatings, and contribute to enhancing the reliability and energy efficiency of wind turbines operating in sandy and desert climates.

CONCLUSIONS AND SUGGESTIONS

According to the results of the conducted studies, leading-edge roughness and erosion caused by sand particles can initially improve the aerodynamic performance of wind turbine blades and increase their power output due to the trip effect. This phenomenon was confirmed by both numerical simulations and experimental investigations. However, once the protective surface layer of the blade is eroded, the erosion rate increases significantly, accelerating surface degradation and eventually leading to blade failure. Experimental studies further demonstrated that the extent of damage experienced by wind turbine blades depends strongly on the size and impact velocity of the sand particles. The experiments conducted in arid areas shows that sand particles can reduce the efficiency of wind turbine up to 45.44%.

Future studies should conduct more on aerodynamic performance of wind turbine blades, more researches create opportunities to know more about blade aerodynamics and can cause further improvement on designing them, and new coatings also required the protective surface layers should improve against erosion by sand.

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