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Stresses and Strains in Biogas Agitation Systems: Understanding, Monitoring, and Mitigating Factors for Efficient and Sustainable Biogas Production

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ABSTRACT: Agitation systems are crucial components in biogas digesters, ensuring optimal mixing of the digestate to maximize biogas production. However, these systems are subject to various mechanical stresses and strains, such as bending, shear, torsional, and centrifugal stresses, which can lead to deformation, inefficiencies, and component failures. Bending stress, caused by forces acting perpendicular to the shaft, can result from uneven digestate distribution or shaft misalignment, leading to reduced mixing efficiency and potential shaft fractures. Shear stress, from impeller blades and motor torque, contributes to impeller wear and shaft fatigue. Torsional stress, due to motor torque, can cause the shaft to twist and initiate fatigue cracks. Centrifugal stress from rotating impellers also plays a role in deformation and added shaft stress. These mechanical issues can lead to reduced biogas production, increased energy consumption, and higher operational costs. Effective design choices, such as selecting appropriate impeller types and materials, and operational practices, including proper alignment and routine monitoring, are crucial for minimizing these stresses. Implementing a comprehensive maintenance strategy that includes preventive maintenance schedules, regular inspections, and the use of sensors for real-time monitoring can significantly enhance the reliability and longevity of biogas agitation systems. This approach ensures efficient mixing, optimal biogas production, and a more sustainable biogas production process.

KEYWORDS: biogas production, agitation systems, stress-strain, efficiency, renewable energy, preventive maintenance.

I. INTRODUCTION

Biogas, a renewable energy source derived from organic matter decomposition, is attracting significant interest in reducing reliance on fossil fuels. However, efficient biogas production hinges on maintaining a homogeneous mixture within the biogas digester, a large tank where the organic material undergoes decomposition [1-7]. This is where agitation systems play a critical role. Factors directly affecting the mixing efficiency [8-10] in the digester include impeller design, bottom clearance, inter-impeller clearance, impeller eccentricity, and slurry rheology. Previous studies have shown that increasing the rotational speed of impellers can prevent dead zones, nutrient segregations, and non-uniform dispersion. However, on the other hand, high mixing speeds can degrade the productivity of bacteria in the digestion process, as these microorganisms are susceptible to high shear stresses and increase operational costs [11, 12]. These systems are equipped with rotating impellers, that continuously stir the digestate (the decomposing material) within the tank [13-17]. This agitation serves several crucial purposes. It enhances mass transfer by facilitating the movement of nutrients and microorganisms throughout the tank, optimizing the biological conversion process. Agitation also prevents stratification, where heavier solids settle at the bottom and lighter materials form a layer on top. Disrupting this stratification ensures all components remain well mixed for optimal biogas production. Additionally, agitation improves heat distribution by helping to spread the heat generated during decomposition, creating a stable thermal environment for the bacteria [5, 7].

While vital for efficient biogas production, agitation systems are constantly under stress. The continuous mixing action subjects these systems to various types of stresses and strains, including bending stress (caused by uneven material distribution or shaft misalignment) [18, 19], shear stress (from the impeller blades on the digestate and within the shaft) [4, 20], torsional stress (the twisting force on the shaft due to rotation), and centrifugal stress (outward forces generated by the rotating impeller on itself and the shaft). If not addressed, these stresses can lead to reduced mixing efficiency due to worn impellers or shaft misalignment, increased energy consumption due to inefficient mixing, and even premature component failure from cracks, fractures, or bearing wear, resulting in unplanned downtime.

To prevent these issues, integrating sensors into biogas mixing systems can significantly enhance maintenance efficiency and reduce costs by providing real-time monitoring and early detection of potential problems. Sensors can monitor various parameters, including temperature, vibration, and alignment, allowing for immediate identification of abnormal conditions that could indicate wear or damage. For instance, temperature sensors can detect overheating in bearings, while vibration sensors can identify imbalances in the impeller or misalignment in the shaft. By continuously collecting and analyzing data, these sensors enable predictive maintenance, allowing operators to address issues before they lead to failures [21-25].

Advancements in computer-aided engineering also offer powerful tools to improve the design of biogas agitation systems. Computational Fluid Dynamics (CFD) allows engineers to simulate flow patterns within the digester virtually [26-27]. This helps optimize impeller design and placement to achieve efficient mixing and minimize areas where the digestate remains stagnant. Additionally, CFD simulations can predict the distribution of shear stress throughout the tank, enabling the design of impellers that minimize excessive shear, which can harm the delicate bacteria responsible for biogas production [4]. Finite Element Analysis (FEA) takes a different approach, focusing on stress analysis within the agitation system components [28, 29]. By analyzing the forces acting on the impeller, shaft, and bearings, FEA allows engineers to identify potential weak points and design these components to minimize bending, shear, torsional, and centrifugal forces. This improves the agitation system's overall efficiency and extends its lifespan by minimizing stress-related failures [17, 30-35]. Both CFD and FEA offer significant benefits for designing biogas agitation systems. These tools can drastically reduce the need for physical prototypes, saving time and resources during the design phase. More importantly, they allow for iterative design modifications and stress analysis, leading to optimized systems with superior mixing efficiency, reduced stress on components, and extended lifespans. This ultimately translates to more efficient and reliable biogas production, contributing to a more sustainable and cost-effective renewable energy source.

This paper aims to provide critical guidelines for minimizing stresses and strains on agitation systems specifically designed for biogas applications. We will explore the different types of stresses affecting these systems, design considerations for impellers, shafts, and materials to optimize stress resistance, best practices for operating agitation systems to minimize stress during operation, and the development of a comprehensive preventative maintenance strategy for biogas agitation systems, incorporating techniques to detect and address potential issues before they lead to failures. By implementing these recommendations, operators of biogas plants can ensure their agitation systems operate efficiently and reliably over a longer lifespan, translating to optimized biogas production, reduced downtime, and enhanced process stability, ultimately contributing to a more sustainable and cost-effective renewable energy source.

II. SOURCES OF STRESS AND STRAIN IN BIOGAS AGITATION SYSTEM

Biogas agitation systems are the workhorses of biogas digesters, constantly churning the decomposing organic material (digestate) to ensure optimal biogas production. However, this continuous operation exposes these systems to various stresses and strains, which can lead to deformations and, ultimately component failures. Understanding the root causes of stress and strain in biogas agitation systems is crucial. Bending stress arises when a force acts perpendicular to the shaft, causing it to bend (**Figure 1**). Uneven digestate distribution, shaft misalignment, or off-center loads can all induce bending stress. A bent shaft can significantly impact mixing efficiency as the impeller struggles to stir the digestate properly. Additionally, excessive bending can lead to increased vibration and, in extreme cases, even shaft fractures, causing complete system breakdown [14, 36].

On the other hand, shear stress is caused by a force acting parallel to the surface of a material (**Figure 1**). Biogas agitation systems experience shear stress in two ways. The impeller blades exert a shearing force on the digestate as they rotate, breaking down solids and promoting mass transfer. This shear stress is essential for efficient mixing. However, excessively high levels can lead to impeller wear, as the constant shearing action erodes the blades over time. Shear stress is also present within the shaft itself due to the torque transmitted from the motor. This cyclic shear stress can contribute to metal fatigue, initiating cracks that can grow and eventually lead to shaft failure.

Torsional stress is a twisting force acting along the shaft's longitudinal axis (**Figure 1**). The primary culprit here is the motor torque required to rotate the impeller and overcome the resistance of the digestate. Excessive torsional stress can cause the shaft to twist slightly, although this might be within acceptable limits, during normal operation. The more concerning consequence is the potential for fatigue cracks. Repeated torsional stress can initiate cracks within the shaft material. These cracks can propagate due to fatigue, potentially leading to catastrophic failure. Additionally, in systems

where a keyway connects the shaft to the impeller, excessive torsional stress can cause the keyway to shear, disconnecting the impeller from the shaft altogether [26]. Finally, centrifugal stress arises from the outward force experienced by a rotating object (**Figure 1**). In biogas agitation systems, this stress originates from the rotating impeller itself. Centrifugal stress is crucial for proper mixing as it helps distribute the digestate throughout the tank. However, excessively high rotational speeds can cause the impeller blades to deform outwards due to centrifugal stress, hindering their mixing performance. Furthermore, the centrifugal force acting on the impeller is transmitted to the shaft, adding to the overall stress it experiences [35, 37]. By understanding these various sources of stress and strain, operators of biogas plants can take proactive measures to minimize their impact. This will not only ensure the long-term reliability and performance of their agitation systems but also contribute to efficient and sustainable biogas production [18, 28].

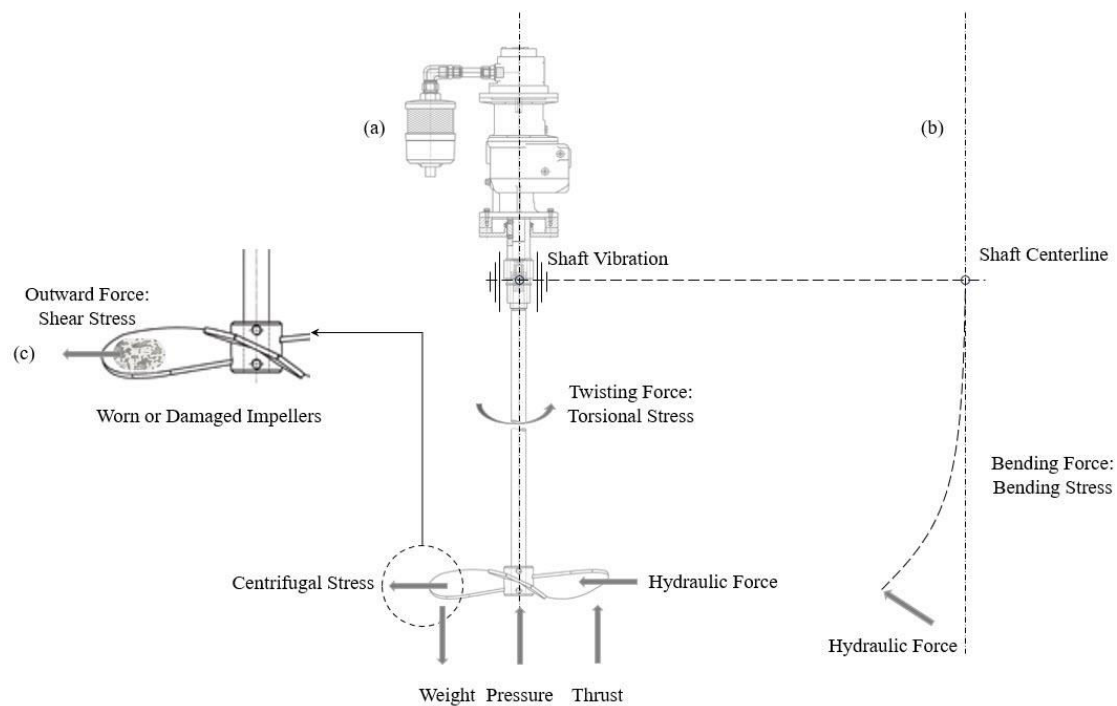


Fig. 1. Stresses acting on agitator shaft.

III. IMPACT OF STRESSES AND STRAINS ON BIOGAS AGITATION SYSTEMS

Excessive stresses and strains on biogas agitation systems can lead to various consequences, affecting both performance and longevity. These consequences manifest in several key areas. Reduced mixing efficiency is a primary concern [4, 14, 17, 26]. Worn or damaged impellers (**Figure 1c**), a consequence of shear stress, become less effective at breaking down solids and promoting mass transfer within the digestate. This leads to uneven mixing, with pockets of high and low nutrient or microorganism concentration. Heavier solids can also settle at the bottom due to inadequate mixing, reducing the overall biogas production potential of the available organic material. Additionally, shaft misalignment caused by bending stress can hinder the impeller's ability to properly stir the digestate, further compromising mixing efficiency (**Figure 2**).

The inefficiency caused by stresses and strains also increases energy consumption [19, 20]. When worn impellers or misaligned shafts hinder mixing, the motor must work harder to maintain the required flow pattern within the digester. This translates to higher energy draw by the motor to overcome the resistance of poorly mixed material, leading to increased operational costs. Furthermore, excessive stresses, particularly bending and shear stress, can accelerate wear and tear on bearings. Increased friction due to worn bearings translates to higher energy consumption by the motor as it struggles to maintain impeller rotation. For agitation mixing systems in biogas tanks, selecting the appropriate bearing type is crucial for reliable and efficient operation. Spherical roller bearings are commonly used due to their ability to handle heavy loads and misalignment. Still, other types like cylindrical roller bearings, tapered roller bearings, deep

groove ball bearings, and thrust ball bearings may also be used depending on specific application requirements. Proper sealing, corrosion resistance, and lubrication (**figure 3**) are essential considerations in this environment.

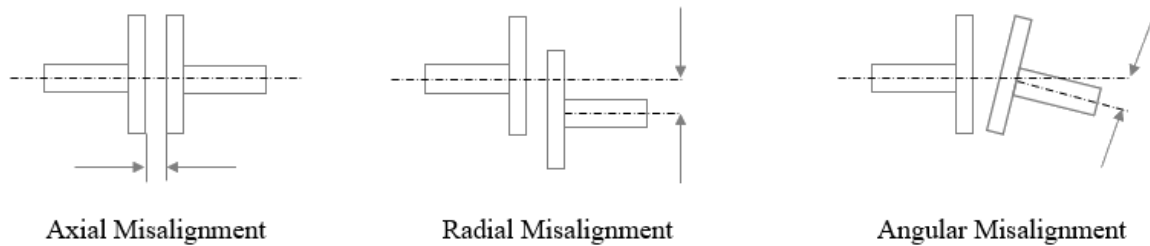


Fig. 2. Shaft misalignment.

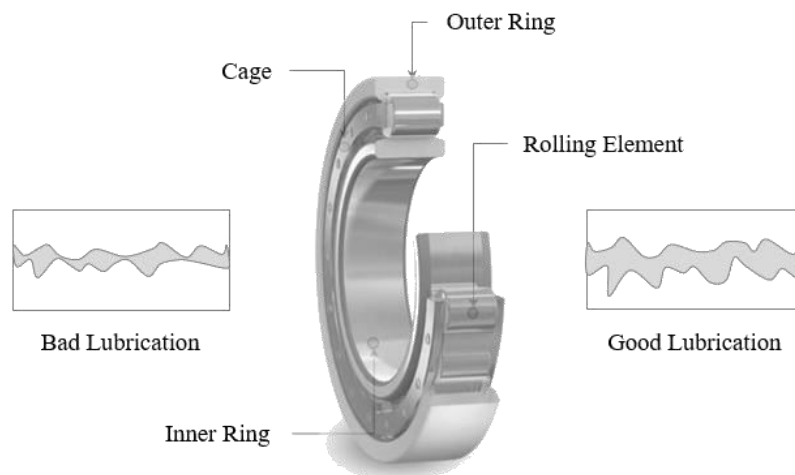


Fig. 3. Bearing lubrication (Bad and Good Lubrication).

Perhaps the most concerning consequence of unaddressed stresses and strains is the potential for component failure. This can lead to unplanned downtime, digestate leakage, and even safety hazards [18, 29]. Excessive stress can cause cracks in impeller blades, eventually leading to complete fracture and breakdown. Similarly, bending, torsional, and fatigue from cyclic shear stress can all contribute to shaft failure, causing a catastrophic system shutdown. **Appendix A** highlights how cracks can develop on the shaft of mixing systems under different types of loads: bending, torsion, and vibration.

Understanding the mechanisms behind crack formation under each load type is crucial for implementing appropriate maintenance and design measures to prevent shaft failures and ensure the reliability of biogas mixing systems. Worn or damaged bearings due to stress can seize up, stopping impeller rotation and requiring immediate maintenance (**Figure 4**). Digestate leakage can occur due to seal failure caused by stress, posing environmental concerns and necessitating repairs, further extending downtime. In the worst-case scenario, catastrophic component failure, such as shaft fractures, can pose safety threats to personnel working near the digester. Finally, inadequate mixing due to stress-induced issues can disrupt the biological process within the digester, which relies on a well-mixed environment for optimal conversion of organic matter to biogas [1, 35, 38]. Poorly mixed digestate may lead to areas with nutrient or microorganism deficiencies, limiting the efficiency of the biogas conversion process.

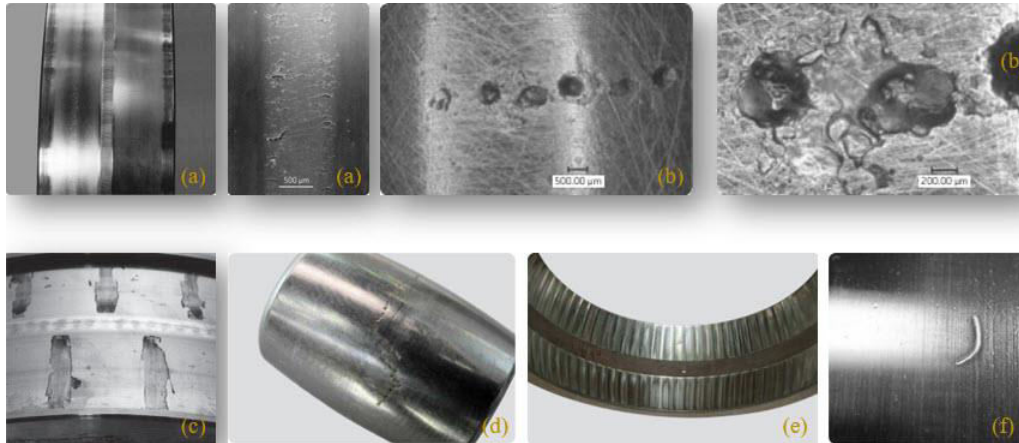


Fig. 4. Types of spherical roller bearing defects/failures (a) micropalls, (b) Excessive current erosion on the roller of a spherical roller bearing, (c) initial patches of etching at rolling element pitch on the inner ring raceways, (d) excessive craters in a zig-zag formation, (e) exposure to excessive vibrations at standmills, (f) overrolled swart/chip will lead to spalling (Source: Bearing damage and failure analysis - SKF).

Additionally, heat generated during decomposition may not be evenly distributed throughout the digester without proper mixing. This can create temperature variations within the digester, potentially impacting the optimal growth and activity of the methanogenic bacteria responsible for biogas production. By understanding the negative consequences of stresses and strains and implementing strategies to minimize them, biogas plant operators can ensure efficient mixing, optimal biogas production, smooth operation, and a safe working environment. **Appendix B** presents the defects and failures in mixing systems according to the predominant loads.

IV. CRITICAL GUIDELINES FOR MINIMIZING STRESSES AND STRAINS

Minimizing stresses and strains on biogas agitation systems requires a two-pronged approach: thoughtful design and meticulous operational practices. The choice of impeller significantly impacts how the digestate is mixed and how stress is distributed within the system. Marine impellers, with their three blades and symmetrical design, are well-suited for biogas applications due to their ability to handle viscous material and minimize off-center loads. Helical ribbon impellers offer a gentler flow pattern, ideal for digesters with sensitive feedstocks or high solids content. While hydrofoil impellers excel in large digesters or those with low-viscosity feedstocks due to their strong axial flow, their design can introduce higher off-center loads. Beyond impeller type, optimizing mixing efficiency involves factors like the number of blades (more blades enhance mixing but increase stress), blade angle (affects flow pattern and mixing intensity), and impeller diameter and rotational speed (careful selection ensures desired flow velocity without excessive stress) [17, 26, 28].

Impellers are central to the functionality of the agitation system. The selection of impeller type - axial flow, radial flow, and mixed flow - depends on the specific mixing requirements. Axial flow impellers, such as marine propellers and hydrofoils, are suitable for large-scale blending and solid suspension, pushing fluid parallel to the impeller shaft. Radial flow impellers, like flat-blade turbines, generate higher shear forces by pushing fluid perpendicular to the shaft, which is useful for more intensive agitation needs. Mixed flow impellers provide a balance between flow and shear, offering versatility in various mixing scenarios. The operational parameters of impellers, such as speed, torque, and power input, are tailored to the fluid's properties to achieve effective mixing. Variable speed drives (VSDs) can optimize energy consumption by adjusting the impeller speed based on real-time mixing requirements. Efficient impeller design reduces energy consumption while maintaining effective mixing, balancing performance with operational costs. Monitoring systems are essential to track energy usage, impeller health, and mixing efficiency, allowing for adjustments to maintain optimal performance.

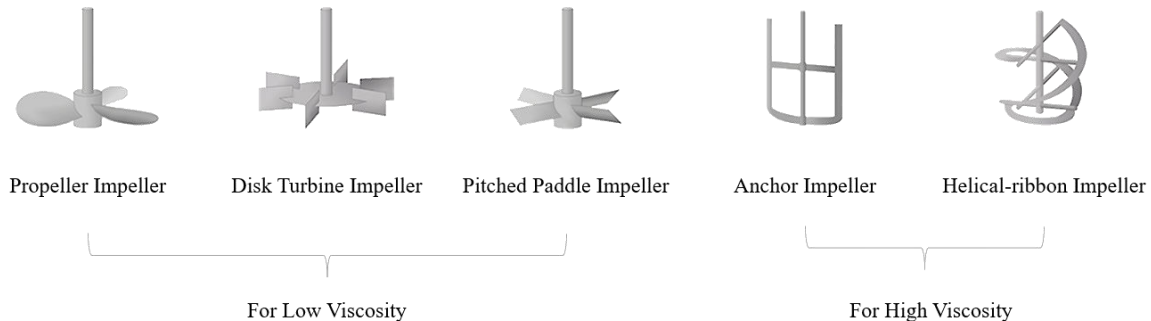


Fig. 5. Different types of impellers according to viscosity.

Material selection for critical components like impellers, shafts, and bearings significantly impacts their resistance to stresses and strains [2]. High strength and fatigue resistance are paramount, particularly for the shaft, which experiences a combination of bending, shear, and torsional stresses. Stainless steel, particularly austenitic stainless-steel grades such as 304 and 316, is widely regarded as one of the most suitable materials for impeller construction in biogas processes (**Appendix C**). These stainless-steel grades offer excellent resistance to corrosion from acidic substances commonly found in biogas substrates, such as hydrogen sulfide (H₂S) and organic acids [2, 6, 19, 39]. Additionally, stainless steel impellers exhibit high strength and durability, ensuring long-term performance and reliability [31, 40]. Another suitable material for impeller construction is high-quality plastics such as polyethylene (PE), polypropylene (PP), and glass fibre-reinforced polymer (GFRP) [8, 27, 38, 41, 42]. These plastics offer excellent resistance to corrosion and erosion and are particularly well-suited for applications where weight reduction and cost-effectiveness are priorities. Furthermore, plastic impellers are easy to manufacture and can be customized to meet specific design requirements. In addition to their resistance to corrosion and erosion, stainless steel and high-quality plastics offer several additional advantages for impeller construction in biogas processes. Stainless steel impellers are highly resistant to bacterial growth, making them suitable for sanitary applications and reducing the risk of contamination in biogas production. Moreover, both stainless steel and plastic impellers are lightweight, which reduces the load on the impeller shaft and bearings, minimizing wear and extending component life. Materials like high-grade stainless steel or special alloys are often preferred choices. Additionally, biogas digestate can be corrosive. Here, materials with high corrosion resistance, such as specific stainless-steel grades or special coatings, are essential to prevent material degradation and premature failure. It's important to consider the specific properties of the digestate being processed. For instance, digestate with high abrasive solids content might necessitate even more wear-resistant materials for impellers [43].

Proper shaft design is critical for minimizing bending and torsional stress. The shaft diameter must be calculated based on the torque requirements of the impeller and the viscosity of the digestate. An undersized shaft is more prone to bending and fatigue failure. As mentioned earlier, high-grade stainless steel or special alloys with good yield strength and torsional properties are preferred materials for shafts. To further minimize stress concentrations, sharp transitions or sudden changes in shaft diameter should be avoided. Smooth transitions or tapered designs are recommended [44]. Beyond design, operational practices play a crucial role in minimizing stresses and strains. Following the manufacturer's recommendations for installation is essential. Improper alignment can introduce significant bending stress on the shaft (**figure 3**). Using qualified personnel and proper tools ensures correct alignment and minimizes the risk of stress-related problems. Implementing overload protection systems for the agitator motor is another best practice. These systems can automatically shut down the agitator if the torque exceeds safe limits due to unforeseen blockages or overloading, preventing excessive stresses from damaging the system. Finally, routine monitoring of key parameters allows for early detection of potential issues and helps prevent major failures. Regularly monitoring vibration levels, motor current, and temperature can help identify problems like shaft misalignment, bearing wear, impeller damage, overloading, or lubrication issues – all of which can contribute to increased stress and wear on the agitation system [43, 44].

Through meticulous consideration of both design and operational practices, operators of biogas plants can markedly mitigate stresses and strains within their agitation systems. This endeavor yields enhanced mixing efficiency, optimal biogas production rates, prolonged longevity of critical components, and fosters a more dependable and sustainable biogas production process. Safety assumes paramount importance in the design of agitation systems for biogas tanks,

owing to the potentially hazardous nature of biogas. Impellers and their associated drive systems must be engineered to preempt ignition sources, incorporating features that render them explosion-proof. Moreover, ensuring structural integrity is essential to withstand fluctuations in operational loads without succumbing to mechanical failures. Furthermore, minimizing noise and vibration is imperative to diminish wear on the system and uphold a safe working environment.

V. CRITICAL GUIDELINES FOR MINIMIZING STRESSES AND STRAINS

Biogas agitation systems, the workhorses of biogas digesters, require a well-defined maintenance strategy to maximize their performance and longevity. This strategy involves a preventative maintenance schedule, proper inspection procedures, and a readily available stock of critical spare parts. The frequency of preventative maintenance tasks hinges on factors like operating hours and the characteristics of the digestate itself. Systems operating for longer durations or processing digestate containing high solids will require more frequent maintenance.

A recommended schedule could include daily visual inspections for leaks, unusual noises, or vibrations; weekly lubrication of bearings; and monthly detailed visual inspections of the impeller, shaft, bearings, and seals, along with vibration monitoring. Quarterly cleaning of the impeller removes accumulated material that can hinder mixing efficiency. Biannual comprehensive inspections by qualified technicians are crucial to identify potential issues early on. Finally, worn, or damaged components like bearings, seals, or the impeller itself should be replaced based on inspection results [45]. Regular visual inspections are a cornerstone of any preventive maintenance program. Key components to focus on include the impeller (checking for cracks, wear, or build-up), the shaft (looking for signs of bending, misalignment, or corrosion), the bearings (listening for unusual noises indicative of wear or damage), and seals (checking for leaks or deterioration). Additionally, vibration monitoring using dedicated equipment is highly recommended. **Table 1** provides a typical maintenance schedule for agitator systems.

Task	Frequency	Description
Visual Inspection	Weekly	Check for signs of wear, corrosion, and damage on all components.
Lubrication Check	Monthly	Inspect lubrication levels and quality in bearings and gearboxes.
NDT Testing	Quarterly	Conduct ultrasonic, magnetic particle, or dye penetrant testing.
Vibration Analysis	Quarterly	Monitor for imbalances or misalignments.
Tightening Bolts	Bi-Annually	Ensure all bolts and fasteners are properly tightened.
Alignment Check	Bi-Annually	Check and correct the alignment of shafts and impellers.
Seal and Gasket Inspection	Bi-Annually	Inspect and replace seals and gaskets as necessary.
Component Cleaning	Monthly	Clean agitator components to prevent sludge build-up.
Component Replacement	As Needed	Proactively replace worn or damaged parts.
Protective Coating Inspection	Annually	Inspect and reapply protective coatings.
Cathodic Protection Check	Annually	Inspect and maintain cathodic protection systems.

Table 1. Typical preventive maintenance schedule.

Increased vibration can be an early warning sign of potential problems, allowing for prompt intervention before they escalate into major issues and downtime [1]. The final piece of the puzzle is maintaining a readily available stock of

critical spare parts. This includes bearings specific to the system's requirements, seals to address leaks promptly, and potentially a spare impeller to minimize downtime during replacement. Other commonly replaced worn components, identified based on the specific system and operating conditions, should also be included in the spare parts inventory [43]. By implementing a comprehensive maintenance strategy that incorporates preventative maintenance schedules, proper inspection procedures, and readily available stock of spare parts, biogas plant operators can ensure the smooth operation, optimal performance, and extended lifespan of their agitation systems. This translates to efficient mixing, increased biogas production, and a more reliable and cost-effective biogas production process [45].

Sensors can be used to effectively monitor defects in mixing systems on biogas tanks. By integrating these sensors into a comprehensive monitoring system, operators can achieve real-time insights into the health of the biogas mixing system. The data collected from the sensors can be analyzed using predictive maintenance software to identify patterns and trends. This enables the maintenance team to perform targeted inspections and interventions, reducing downtime and improving the overall efficiency and reliability of the system. Sensors contributing to detecting and preventing defects in these systems are, vibration sensors, temperature sensors, pressure sensors, ultrasonic sensors, lubrication sensors, corrosion sensors, and load sensors.

By incorporating these sensors into the biogas agitation system, operators can achieve a higher level of monitoring and control, leading to improved reliability, efficiency, and longevity of the equipment. Real-time data from these sensors allows for predictive maintenance, timely interventions, and optimized operational performance, ultimately reducing downtime and maintenance costs.

V. CONCLUSION

In conclusion, the comprehensive exploration of stress and strain in biogas agitation systems underscores the critical importance of understanding, monitoring, and mitigating these factors for efficient and sustainable biogas production. The incessant agitation required for optimal biogas production subjects these systems to various types of stresses – bending, shear, torsional, and centrifugal – which can lead to component failures if left unaddressed. These failures not only disrupt the mixing process but also increase energy consumption and pose safety hazards, ultimately impacting the entire biogas production process. Moreover, the discussion extends beyond engineering concerns, highlighting the broader implications of stress-induced issues on biogas production efficiency and environmental sustainability. Reduced mixing efficiency due to worn impellers or misaligned shafts can lead to uneven digestate distribution, limiting biogas production potential and compromising the effectiveness of the biological process within the digester.

Excessive stresses also accelerate wear and tear on critical components, necessitating frequent maintenance and increasing operational costs. However, by implementing critical guidelines for minimizing stresses and strains, such as thoughtful design considerations, meticulous material selection, and proper operational practices, biogas plant operators can significantly reduce the impact of stress-induced issues. Furthermore, maintenance strategies, incorporating preventive maintenance schedules and sensor-based monitoring systems, offer proactive approaches to identify and address potential problems before they escalate into major failures, ensuring the smooth operation and longevity of biogas agitation systems.

Ultimately, the hypothetical scenario presented demonstrates the tangible benefits of leveraging sensor technology for preventive maintenance in biogas agitation systems. By combining proactive monitoring with predictive maintenance strategies, operators can minimize downtime, optimize maintenance schedules, and enhance biogas production processes' overall reliability, efficiency, and profitability. This integrated approach underscores the importance of adopting cost-effective maintenance practices and harnessing technology to drive sustainable industrial operations.

VI. APPENDIX A: SUMMARY OF POTENTIAL FAILURE MODES FOR VARIOUS COMPONENTS IN AN AGITATOR SYSTEM, ALONG WITH THEIR CAUSES AND EFFECTS

Component	Failure Mode	Causes	Effects
Shafts ^[46-49]	Misalignment	Improper installation, wear, bearing failure	Increased vibration, wear on other components
	Cracking or Fracture	Fatigue, corrosion, excessive loading	System failure, safety hazards
	Corrosion	Exposure to moisture and corrosive substances	Reduced structural integrity, potential failure
Impellers ^[50-53]	Wear	Abrasion by solids, corrosion	Reduced efficiency, imbalance
	Imbalance	Uneven wear, damage	Increased vibration, potential bearing damage
	Cracking	Fatigue, corrosion, excessive loading	Reduced performance, potential failure
Blades ^[49-53]	Wear	Abrasion, corrosion	Reduced mixing efficiency, imbalance
	Cracking or Breaking	Fatigue, impact, corrosion	Reduced performance, potential safety hazards
	Corrosion	Exposure to corrosive substances	Reduced structural integrity, potential failure
Bearings ^[49, 54-56]	Wear	Contamination, inadequate lubrication	Increased friction, heat generation, failure
	Corrosion	Exposure to moisture, inadequate sealing	Reduced lifespan, potential failure
	Misalignment	Improper installation, shaft misalignment	Increased wear, vibration, noise
	Overheating	Insufficient lubrication, excessive loading	Bearing failure, system shutdown
Seals ^[50, 51, 53, 54, 57, 58]	Wear or Degradation	Friction, exposure to chemicals	Leakage, contamination of bearings and lubricants
	Cracking	Aging, exposure to harsh conditions	Loss of seal integrity, contamination
	Leakage	Improper installation, wear, damage	Lubricant loss, contamination
Oil ^[50, 55, 59-62]	Contamination	Ingress of dirt, moisture, chemicals	Reduced lubrication effectiveness, increased wear
	Degradation	High temperatures, oxidation, contamination	Reduced lubrication, increased friction and wear
	Insufficient Levels	Leaks, inadequate maintenance	Increased friction, heat, wear

VII. APPENDIX B: DEFECTS AND FAILURES IN MIXING SYSTEMS ACCORDING TO PREDOMINANT LOADS

Load Type	Defect/Failure	Description
Bending	Shaft Fatigue	The fatigue failure of agitation shafts due to cyclic bending loads leads to cracks (Mode I) and eventual fracture formation [63-66].
	Impeller Warping	It is warping or bending of impellers under bending loads, resulting in uneven mixing, increased energy consumption, and potential damage to the shaft and bearings [67, 68].
	Bearing Misalignment	Misalignment of bearings supporting the agitation shaft due to bending loads, leading to increased friction, premature wear, and potential bearing failure [69-71].
Torsion	Shaft Torsional Failure	Torsional failure of agitation shafts due to excessive torque or torsional stress, resulting in shearing or twisting of the shaft and potentially catastrophic failure (Mode II) [72-76].
	Gearbox Overload	Overloading of gearboxes driving agitation systems leads to torsional stress and potential gear or bearing damage, particularly in high-torque applications [77-78].
	Seal Deformation	Deformation or failure of seals under torsional loads compromises sealing integrity and leads to process fluid leakage or contamination [70, 79, 80].
Vibration	Vibration Fatigue	Fatigue failure of components such as shafts, impellers, or bearings due to excessive vibration, leads to crack initiation and propagation under cyclic loading (Mode III) [64, 81, 82].
	Resonance	Resonance-induced vibration of components at certain frequencies amplifies vibration amplitudes and potentially causes structural damage or premature wear [83-86].
	Bearing Wear	Accelerated bearings wear due to vibration-induced forces, leading to increased friction, heat generation, and potential bearing failure or seizure [87-88].
	Seal Degradation	Degradation of seals under vibration loads, resulting in loss of sealing effectiveness, leakage, and potential contamination of the surrounding environment or process fluid [57, 89-91].

VIII. APPENDIX C: MECHANICAL PROPERTIES AND COSTS

Property/ Characteristic	Tensile Strength (MPa)	Yield Strength (MPa)	Hardness (HB)	Elongation (%)	Density (g/cm ³)	Corrosion Resistance	Cost	Additional Properties	Ref.
304 Stainless Steel	505 - 735	215 - 290	150 - 200	40 - 60	7.9	Good	Moderate	Good balance of ductility and strength	[92-96]
316 Stainless Steel	515 - 760	205 - 275	150 - 220	30 - 45	8	Excellent	High	Enhanced resistance to chlorides and harsh environments	[92-96]
Duplex Stainless Steel	620 - 850	450 - 550	260 - 320	25 - 35	7.8	Excellent	High	Excellent resistance to stress corrosion cracking	[92-97]
Super Duplex Stainless Steel	700 - 950	550 - 700	270 - 350	20 - 30	7.8	Superior	Very High	Superior resistance to pitting and stress corrosion	[92-98]
Coated Carbon Steel	400 - 550	250 - 400	120 - 180	15 - 25	7.8	Good (with coating)	Moderate	Strength depends on coating; cost-effective	[94, 99, 100]
Fiber-Reinforced Plastics (FRP)	100 - 300	70 - 150	-	1-Mαi	1.5 - 2.0	Good	Moderate	Lightweight, customizable shapes	[101-103]
High-Density Polyethylene (HDPE)	20 - 40	15 - 30	40 - 50	> 100	0.95	Excellent	Low	Excellent flexibility and chemical resistance	[104-108]
Cast Iron with Protective Coatings	150 - 350	130 - 310	150 - 220	0.5 - 2	6.8 - 7.8	Moderate (with coating)	Moderate	Durable with proper coating; brittle compared to steels	[109--111]
Titanium	480 - 620	345 - 450	200 - 400	0κτ-25	4.5	Superior	Very High	Outstanding strength-to-weight ratio and corrosion resistance	[112-113]

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