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A Review of Gas Turbine Emissions: From Environmental Challenge to Diagnostic Tool

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Abstract

This review examines the intersection of gas turbine condition-based maintenance and climate change, emphasizing the critical role of emissions monitoring in enhancing operational efficiency and environmental sustainability. Recent research underscores the potential of emissions data to provide insights into combustion stability and operational health, enabling timely interventions to improve turbine performance. The review highlights advancements in emission detection, mitigation strategies, and predictive maintenance methodologies, particularly through the integration of artificial intelligence and data analytics. It notes a significant increase in research publications, reflecting a global commitment to addressing the dual challenges of improving gas turbine efficiency and reducing environmental impact. Furthermore, the review identifies critical gaps in the current understanding of emissions from hot gas path sections and advocates for the development of real-time emission analysis techniques. By leveraging advanced technologies and fostering interdisciplinary collaboration, the gas turbine industry can enhance its contributions to climate change mitigation while ensuring reliable energy generation. This work serves as a roadmap for future research and development efforts aimed at optimizing gas turbine operations and promoting sustainable practices in the energy sector.

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مراجعة لانبعاثات التوربينات الغازية: من التحدي البيئي إلى أداة تشخيصية

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الملخص:

تتناول هذه المراجعة العلاقة بين الصيانة القائمة على حالة التوربينات الغازية وتغير المناخ، مع التركيز على الدور المحوري لرصد الانبعاثات في تعزيز الكفاءة التشغيلية والاستدامة البيئية. تُبرز الأبحاث الحديثة قدرة بيانات الانبعاثات في توفير رؤى ثاقبة حول استقرار الإحتراق الداخلي والكفاءة التشغيلية للتوربينات الغازية، مما يساعد في التخطيط للصيانة في الوقت المناسب لتحسين أداؤها. تُسلّط المراجعة الضوء على التطورات في مجال كشف الانبعاثات، واستراتيجيات التخفيف منها، ومنهجيات الصيانة التنبؤية، لا سيما من خلال دمج الذكاء الاصطناعي وطرق تحليل البيانات. وتُشير إلى زيادة ملحوظة في المنشورات البحثية، مما يعكس التزامًا عالميًا بمعالجة التحدّيين المتمثلين في تحسين كفاءة التوربينات الغازية والحد من تأثيرها البيئي. علاوة على ذلك، تُحدّد المراجعة ثغرات جوهرية في الفهم الحالي للانبعاثات من أقسام مسار الغاز الساخن، وتدعو إلى تحسين تقنيات التحليل الآني للانبعاثات. من خلال الاستفادة من التقنيات المتقدمة وتعزيز التعاون متعدد التخصصات، يمكن لصناعة التوربينات الغازية أن تعزز مساهماتها في التقليل من عوامل او مسبّبات التغيّر المناخي مع ضمان توليد طاقة موثوق. ويمثل هذا العمل خارطة طريق لجهود البحث والتطوير المستقبلية الرامية إلى تحسين تشغيل التوربينات الغازية وتعزيز الممارسات المستدامة في قطاع الطاقة.

وقد تم عرض هذه الورقة العلمية في جلسات المؤتمر الدولي للطاقة المتجددة والنفط والغاز وتغير المناخ "أيريقو" في الفترة 25-27 ابريل 2026م. طرابلس – ليبيا

الكلمات المفتاحية: التوربينات الغازية، رصد الانبعاثات، تغير المناخ، الصيانة التنبؤية، الاستدامة البيئية

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1- Introduction

Gas turbines are machines that generate energy to rotate a shaft, which subsequently powers other rotating machinery such as compressors and generators. In the oil and gas sector, for example, gas turbines serve as prime movers in the gas transportation process through pipelines and in electrical power generation. However, their operation presents considerable environmental challenges primarily due to the emissions they generate. Historically, the mitigation of greenhouse gases like carbon dioxide (CO_2), alongside hazardous air pollutants like nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (UHC), and particulate matter has dictated strict global regulatory standards [1]. This regulatory landscape has driven intensive research into clean combustion architectures such as Dry-Low Emission (DLE) and lean pre-mixed combustors which face inherent risks regarding flame stability and localized engine operability [2]. Despite their negative environmental impact, a compelling paradigm shift has emerged, leveraging exhaust gas chemistry as a non-invasive diagnostic tool. Rather than treating emissions purely as a regulatory liability, modern architectures can capture real-time exhaust composition trends to infer localized engine health [3]. Anomalous fluctuations in emission profiles directly correlate with specific degradation mechanisms like compressor fouling, burner degradation, fuel nozzle erosion, or sub-optimal combustion staging [4]. By pairing continuous monitoring systems or virtual predictive models with advanced analytical frameworks, operators can map gas turbine performance footprints back to physical root causes [5].

This review highlights the transition from using pollutant signatures solely for regulatory compliance to leveraging them as valuable data for managing system health. It explores how the analysis of gas turbine emissions can help identify internal engine issues, thereby bridging the gap between emission monitoring and diagnostic practices.

2- Impacts and Causes of Emissions

Emissions from gas turbines are unavoidable, and their environmental impact has been a focus of concern for many environmentalists and organizations. Nonetheless, scientific research has shed light on the root causes of excessive emissions and their negative effects on the machinery itself. For instance, research studies highlighted that the type of fuel or gas utilized in gas turbines significantly influences emissions [6], [7], [8], [9]. Another study highlighted how fuel quality, especially hydrogen content, affects combustion stability and characteristics, indicating that higher

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hydrogen levels can lead to increased instability modes [10]. The difficulties in maintaining stable operation due to variations in fuel composition and supply systems were also addressed [11]. Furthermore, the combustion dynamics of hydrogen/methane flames within a lean-direct injection gas turbine combustor were examined [12]. Their findings revealed that fluctuations in fuel flow impact flame response and stability, as measured by flame transfer functions (FTF) across different hydrogen/methane ratios. Their results showed that higher ratios of hydrogen/methane resulted in increased frequency of longitudinal thermoacoustic instability, underscoring the necessity for careful fuel management to ensure stable combustion. Moreover, in a recent investigation, the effects of wall heat loss on the stability of NH_3-CH_4-air flames and emissions in a gas turbine combustor were explored [13]. The authors discovered that local extinction phenomena considerably affected flame dynamics, leading to increased N_2O concentrations while reducing NO levels. They created a chemical reactor network model to identify emission characteristics, emphasizing the significance of understanding how heat loss impacts combustion stability. Additional research examined variations in combustion performance with different hydrogen to carbon monoxide ratios, indicating that elevated levels of hydrogen or carbon monoxide could damage fuel nozzles due to flashback [14].

The findings from these studies underscore the complexity of hot gas path failures in gas turbines. By comprehending the various failure mechanisms and their underlying causes, researchers and engineers can formulate more effective maintenance strategies and design enhancements to improve the reliability and efficiency of gas turbine systems.

3- Emission Detection and Mitigation

Gas turbines are a significant source of air pollutants and greenhouse gas emissions, leading to heightened regulatory scrutiny and targeted research initiatives. While these research efforts focus on mitigating environmental impacts, they also provide valuable insights for performance monitoring. As depicted in figure (1), the current emissions estimates for existing gas turbines were combined and the effects of emission control techniques on emissions, cycle performance, and maintenance intervals were examined [15]. This information aids in monitoring gas turbine performance by offering benchmark data on typical emissions, the correlation between emissions and performance/maintenance, and the influence of various fuels.

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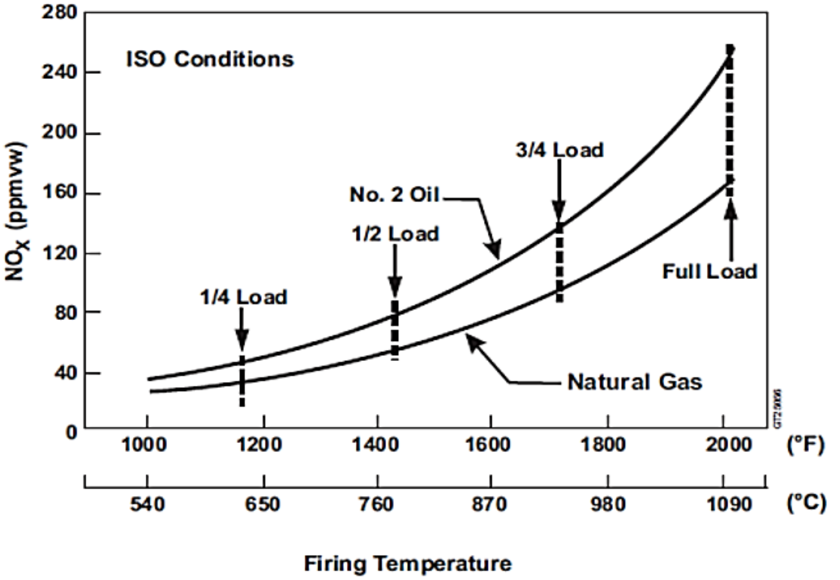

Figure (1): Typical NO_x emissions of a gas turbine [15]

By comparing actual emissions against these summarized data, operators can identify deviations that may signal reduced efficiency, the necessity for maintenance, or improper operational practices.
Detecting and understanding combustion instability in gas turbines, along with effective emissions measurement and optimization strategies, are crucial for improving operational stability and reducing emissions. Numerous studies have examined methods to assess and enhance combustion dynamics for more efficient and reliable gas turbine operation

An early study discussed the practical limitations of emission control technologies, addressing issues related to sampling, accuracy, and data recording, and proposed improvements based on three years of continuous testing [16]. The design and capabilities of test benches focused on accurate emission measurements, particularly for NO_x and CO were emphasized [17]. Similarly, a test cell for micro-gas turbines was successfully designed for emission and performance testing, achieving satisfactory results [18]. A combustion tuning methodology for industrial gas turbines was introduced, demonstrating low dynamic pressure fluctuations (0.08 psi or less) in a double-swirl combustor, which significantly reduced NO_x emissions from 18 to 2.2 ppm at base load [19]. The authors highlighted the importance of monitoring combustion

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pulsation for stable operation. Further evaluations on syngas turbine flame stability revealed optimal operating conditions correlated with temperature and emissions, noting that high nitrogen levels could destabilize flames [20]. An optical approach to characterize combustion fluctuations was tested, utilizing fast infrared imaging and wavelet analysis to identify oscillations at low frequencies around 82 Hz and 146 Hz [21]. The NH_3-air combustion efficiency was examined, finding that combustor inlet temperature significantly influenced NOx and unburned NH_3 emissions [22]. The authors also studied NH_3-CH_4-air combustion, noting that increased NH_3 ratios affected NO emissions. The combustion performance in miniature gas turbines with a variable geometry combustion chamber was explored, achieving over a 40% reduction in NO_x emissions [23]. Additionally, a review of low-emission combustion technologies for modern aero gas turbines assessed key technologies and their emissions mitigation potential [24]. Numerical analyses indicated that combustion efficiency and pressure drop increased with higher excess air ratios (EAR), while CO_2 and unburned hydrocarbon emissions decreased, although NO_x emissions varied with EAR levels [25]. The combustion of technical glycerol in micro gas turbines was also investigated, identifying mechanisms to reduce NO_x and particulate matter emissions [26]. The authors found significant reductions using highly oxygenated fuels, indicating altered air-fuel ratios could suppress emissions. A conical radial swirl-stabilized combustor designed through additive manufacturing helped reduce NO_x and CO emissions [27]. Lastly, a method for early detection of combustion instability using spectral centroid and spectral spread analysis was proposed, outperforming conventional techniques in speed and accuracy, although it may misclassify unstable flames during multi-mode combustion instability [28]

4- Emission Prediction and Condition Monitoring

Understanding the normal emission profiles of gas turbines is essential for effectively monitoring combustion instability. This knowledge allows engineers to identify deviations, diagnose problems, and implement corrective actions, thereby maintaining the health and efficiency of gas turbine systems. An early foundational study examined gas turbine engine emissions in relation to operating parameters, fuels, and environmental factors [29]. The authors utilized mobile laboratories and fixed systems for measuring various emissions and processing data to ensure accurate emissions calculations. For related purpose, an innovative emission

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prediction model that accounts for the independent behavior of main and pilot flames was introduced, achieving a commendable accuracy in predicting NO_x emissions with a deviation of ±13% [30]. This progression in research demonstrates the ongoing interest in gas turbine emissions and combustion instability, highlighting the importance of continuous advancements in monitoring and predictive methodologies.

5- AI-Driven Emission-Based Maintenance

The use of AI techniques in gas turbine maintenance has attracted significant interest from researchers, leading to the development of various AI-driven condition-based maintenance (CBM) strategies. Tackling the challenges associated with existing NO_x estimation methods, which often rely on complex mechanisms and exhibit low accuracy, a novel neural network (NN) model for estimating NO_x emissions from gas turbines was proposed, utilizing ambient and boundary parameters as inputs [31]. This model included an adjustable and monitorable intermediate layer to improve estimation accuracy, achieving an enhancement of approximately 2.23% and halving the estimation error compared to traditional methods. However, the variability in data distributions across different gas turbine models and installation environments poses significant challenges for model applicability and generalizability. Each gas turbine model has unique specifications, materials, and operational parameters, leading to variations in performance metrics, including emission levels. Stacked ensemble learning, which employs decision-level data fusion, shows promise in predictive maintenance for mechanical systems, particularly when data from different sensing modalities are available [32]. This success encourages the exploration of data fusion techniques in gas turbine maintenance, where integrating data from diverse sources such as vibration, temperature, pressure, flow rate, emission sensors, historical performance data, and environmental conditions could enhance failure identification and degradation pattern recognition. By adopting these advanced methodologies, the gas turbine industry could unlock new opportunities for optimized operational efficiency and proactive maintenance actions. As depicted in figure (2), a recent extensive state-of-the-art literature review provided a comprehensive overview of how literature reviews help researchers and practitioners involved in gas turbine CBM understand the current practices and pinpoint any future opportunities based on the categorization of the considered publications including those related to gas turbine emissions [33]. The figure illustrates

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how the categorization of targeted publications helps researchers and practitioners push the limits of gas turbine CBM and efforts to mitigate environmental effects. For example, the Prediction and Monitoring category exposes the failed components addressed and operational parameters used, advancing the AI-Driven Maintenance efforts by exploring the proposed prognostic and monitoring methods. This ultimately aims to enable more advanced, robust maintenance strategies based on appropriate AI models

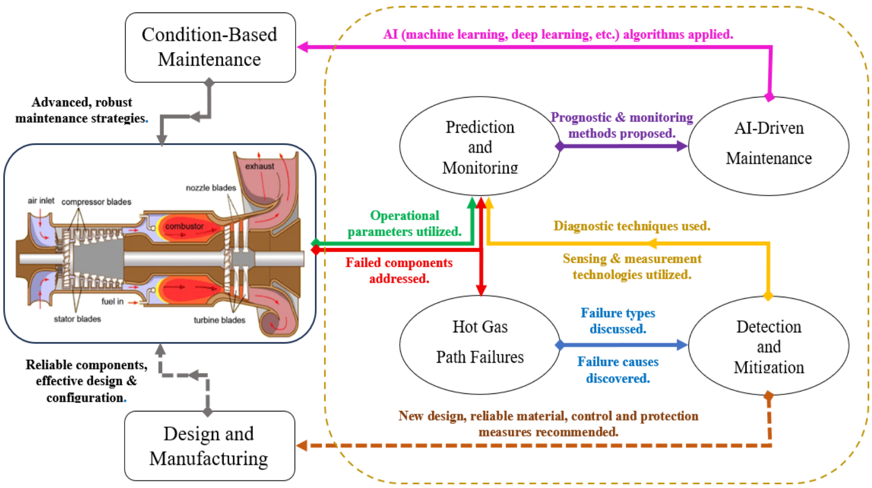

Figure (2): How literature reviews help in obtaining reliable gas turbines with minimum negative impact [33]

. On the other hand, the Hot Gas Path Failures category, by revealing the failed components addressed, enhances the Detection and Mitigation studies. This is achieved by exploring the diagnostic techniques used and the failed components addressed, which can lead to improvements in Prediction and Monitoring methods through the discovery of reliable diagnostic techniques and sensing/measurement technologies. Alternatively, it can inform enhancements to Design and Manufacturing efforts by recommending new designs, reliable materials, and improved control and protection measures, aiming to achieving reliable components and effective design configurations. Overall, the figure demonstrates the interconnected nature of the different research and development efforts, where insights and advancements in one area can drive progress in others, ultimately pushing the boundaries of gas turbine CBM and environmental

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impact mitigation. The authors also identified the emission monitoring as a critical gap of research and recommended future research focusing on developing real-time emission analysis techniques, integrating advanced sensors and data analytics to enable predictive maintenance strategies aiming for integral gas turbines with minimum environmental impacts.

Table (1) provides an overview of various studies concerning gas turbine emissions, categorized by key focus areas and study outcomes, facilitating a clearer understanding of the current research landscape in this field. This summary serves as a valuable resource for researchers and practitioners aiming to enhance their knowledge and address the challenges associated with gas turbine emissions.

Table (1): Summary of Studies on Gas Turbine Emissions

Reference	Research focus	Research outcomes
[6] – [9]	Fuel type	Fuel type significantly influences emissions
[10], [11]	Fuel quality	Turbine fuel composition and Hydrogen content influence combustion instability
[12]	Fuel flow	Fluctuations in fuel flow impact flame response and stability
[13]	Effects of combustor wall heat loss on the combustion stability	Local extinction phenomena affects flame dynamics, increases N_2O levels while reducing NO levels
[14]	Variations in combustion performance	Elevated levels of Hydrogen or Carbon monoxide could damage fuel nozzles due to flashback
[15]	Emissions estimation	Emissions estimation aids in monitoring gas turbine performance by offering benchmark data on typical emissions
[16]	The practical limitations of emission control technologies	Addressing sampling, accuracy, and data recording issues and proposing improved continuous testing
[17], [18]	Emissions Measurements	Design of test benches and cells for gas turbine accurate emission measurements
[19]	Tuning dynamic pressure in a gas turbines combustor	Low dynamic pressure fluctuations significantly reduce NOx emissions, and monitoring combustion pulsation is important for stable operation
[20]	Turbine flame stability	Optimal operating conditions are correlated with temperature and emissions, and high nitrogen levels could destabilize flames

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Reference	Research focus	Research outcomes
[21]	Combustion fluctuations	Testing an optical approach to characterize combustion fluctuations utilizing fast infrared imaging and wavelet analysis
[22]	NH_3-air combustion efficiency	Combustor inlet temperature significantly influenced NO_x and unburned NH_3 emissions
[23]	Effects of combustion chamber geometry	The combustion performance in gas turbines with a variable geometry combustion chamber could achieve over a 40% reduction in NOx emissions
[25]	Impact of excess air ratios (EAR)	Combustion efficiency and pressure drop increase with higher EAR, while CO_2 and UHC emissions decrease, and NO_x emissions varied with EAR levels
[27]	Emission reduction	A conical radial swirl-stabilized combustor designed through additive manufacturing helped reduce NO_x and CO emissions
[28]	Early detection of combustion instability	Spectral centroid and spectral spread analysis outperforms conventional techniques in speed and accuracy, with limitations during multi-mode combustion instability
[29], [30]	Emissions prediction and monitoring	Mobile laboratories and fixed systems for measuring various emissions, processing data to ensure accurate emissions calculations and an innovative model for emission prediction
[31], [32]	AI-driven emission-based maintenance	The application of neural networks and ensemble learning for emission estimation and support decision-making

6- Results and Discussion

By reviewing and synthesizing the research papers examined, the study has generated substantial knowledge and insights into the topic of gas turbine emissions. The selected studies illustrate contributions from various authors across different countries, highlighting collaborative efforts and a global commitment to this research area. As depicted in figure (3), the data reveals a notable increase in publications, particularly leading up to 2026, indicating a growing emphasis among researchers on the importance of monitoring and controlling gas turbine emissions to promote a cleaner environment while enhancing the efficiency and

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reliability of these machines. This rise in publications is closely linked to the principles of the industrial revolution, which advocate for the integration of advanced technologies, including powerful computing capabilities, reliable sensing technologies, robust data analysis techniques, and AI algorithms. These innovations enable the effective collection and analysis of emission data generated by gas turbines, facilitating improved monitoring and predictive maintenance strategies.

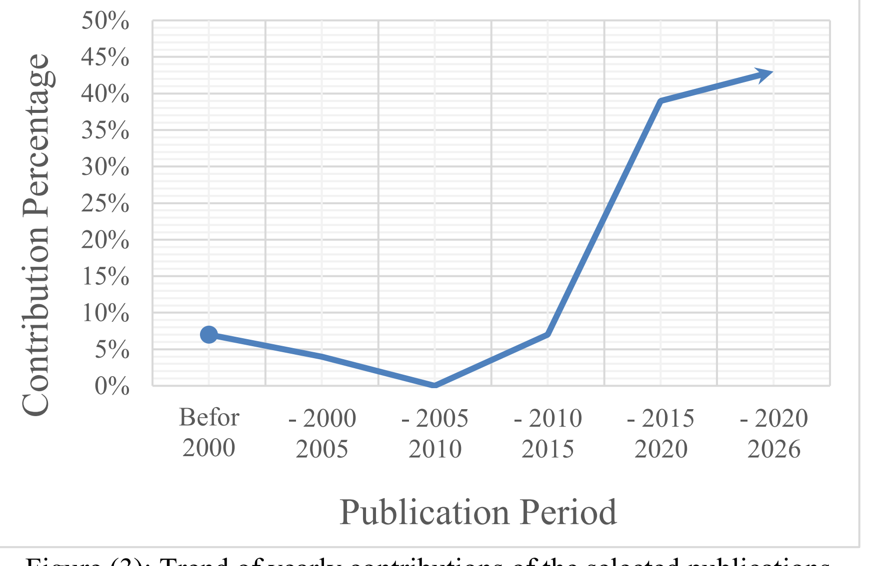

Figure (3): Trend of yearly contributions of the selected publications

Furthermore, the insights and recommendations derived from the literature review provide valuable guidance for future research and development in gas turbine CBM and its global impact. The review encompasses a broad spectrum of techniques for measuring, detecting, monitoring, predicting, and controlling emissions, addressing current challenges and limitations while offering a roadmap for researchers and practitioners to explore innovative solutions. This progress is essential for advancing both gas turbine CBM and efforts to combat climate change. The interdisciplinary nature of emission condition monitoring is emphasized, highlighting the significance of the issue, its major consequences, and the necessity for collaborative efforts across various fields to propel the discipline forward. A critical gap has been identified in the CBM of gas turbine hot gas path sections. Just as medical diagnostics detect health issues through bodily outputs, potential gas

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turbine failures can be identified by analyzing exhaust emissions. These emissions provide crucial insights into the combustion process, revealing early indicators of damage such as incomplete combustion, fuel inefficiencies, or component degradation.

Future research should prioritize the development of real-time emission analysis techniques, integrating advanced sensors and data analytics to enable predictive maintenance strategies. This approach not only enhances the reliability of gas turbines but also contributes to broader climate change mitigation efforts by reducing harmful emissions and promoting sustainable practices in the energy sector.

7- Conclusion

In summary, this review highlights the critical role of gas turbine emissions in both operational efficiency and environmental impact. The insights gathered from various studies underscore the importance of monitoring and analyzing emissions not only for regulatory compliance but also for enhancing the health and performance of gas turbine systems. As the demand for cleaner energy solutions intensifies in the context of climate change, the integration of advanced technologies including AI, data analytics, and real-time monitoring becomes essential. These innovations facilitate the development of effective CBM strategies that can identify potential failures and optimize performance, ultimately contributing to reduced emissions and a more sustainable energy landscape. Future research must continue to focus on refining emission analysis techniques and exploring data fusion methodologies to enhance predictive maintenance capabilities. By bridging the gap between emissions monitoring and diagnostic practices, the gas turbine industry can significantly improve operational reliability while addressing the pressing challenges of climate change. Collaborative efforts across disciplines will be vital in driving forward the advancements necessary for a cleaner and more efficient energy future.

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