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Analysis of Performance and Emission Characteristics of Gas Turbines Fuelled by Biofuel

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Abstract:
This study investigates the performance and emission characteristics of biofuel blends in gas turbines, aiming to evaluate their feasibility as alternative fuels in aviation and power generation applications. With increasing environmental concerns and regulatory pressures to reduce greenhouse gas emissions, biofuels have emerged as a promising solution to enhance sustainability in the energy sector. The research examines various biofuel blends, including biodiesel and renewable diesel, in combination with conventional fossil fuels. Experimental analyses are conducted to assess key performance indicators such as thermal efficiency, power output, and combustion stability. Additionally, emission profiles, including nitrogen oxides (NOx), carbon monoxide (CO), and particulate matter (PM), are evaluated to determine the environmental impact of using biofuels in gas turbines. Results indicate that specific biofuel blends can achieve comparable performance to traditional fuels while significantly reducing harmful emissions. This study provides valuable insights into the viability of biofuel integration into gas turbine operations, contributing to the ongoing pursuit of cleaner and more sustainable energy solutions. The findings highlight the potential for biofuels to play a crucial role in reducing the carbon footprint of gas turbines and promoting greener energy technologies.

1. Introduction

The urgent need for sustainable energy solutions has led to increased interest in biofuels as alternatives to conventional fossil fuels, particularly in applications such as aviation and power generation. Gas turbines, known for their efficiency and reliability, are widely used in various industries, including electricity generation and aircraft propulsion. However, their dependence on fossil fuels contributes significantly to greenhouse gas emissions, prompting the exploration of renewable fuel options that can reduce environmental impact while maintaining performance.

Biofuels, derived from biological materials such as plants and waste, offer a promising pathway to mitigate the environmental challenges associated with traditional fuels. These renewable energy sources can provide similar energy content to fossil fuels, making them suitable for gas turbine applications. Blending biofuels with conventional fuels has emerged as a practical approach to enhance fuel properties, optimize combustion processes, and achieve significant reductions in harmful emissions, including carbon dioxide (CO_2), nitrogen oxides (NOx), and particulate matter (PM).

This study aims to investigate the performance and emission characteristics of various biofuel blends when utilized in gas turbines. By evaluating a range of biofuel formulations, including biodiesel and renewable diesel, the research seeks to identify optimal blends that achieve comparable performance to conventional fossil fuels while minimizing environmental impact. Experimental analyses will focus on critical performance metrics, such as thermal efficiency, power output, and combustion stability, as well as comprehensive emission profiles under different operating conditions.

The findings from this research will contribute valuable insights into the potential of biofuels as sustainable alternatives for gas turbines, supporting the transition towards greener energy technologies. As the energy landscape continues to evolve, understanding the performance and emissions characteristics of biofuel blends will be essential for developing effective strategies to reduce the carbon footprint of gas turbine operations and promote a more sustainable energy future.The findings of this research are anticipated to contribute valuable insights to the aviation and power generation industries, offering a scientific foundation for the integration of biofuels in gas turbine applications. The assessment of performance and emissions characteristics is crucial for both environmental sustainability and compliance with increasingly stringent regulatory standards. By shedding light on the viability of biofuel blends, this research seeks to inform stakeholders, policymakers, and industry professionals about the potential of biofuels in mitigating the environmental footprint of gas turbine operations. The outcomes of this study have broader implications for the transition towards cleaner and more sustainable energy sources in critical sectors that heavily rely on gas turbine technology.

2. Existing Experimental Techniques

Fuel performance is measured in terms of brake thermal efficiency (BTE), brake-specific energy consumption (BSEC), brake-specific fuel consumption (BSFC), indicated mean effective pressure (IMEP), in-cylinder pressure measurement, heat-release rate and ignition-delay analysis using a wide range of diesel engines [20]. Among the most used diesel engines for research are Cussons and Kirloskar engines, as shown in Figure 1. Different types of dynamometers are used to measure the power and torque of the engine under various operating conditions. Performance maps can be generated to analyze parameters such as torque, power, fuel consumption and efficiency under varying conditions to obtain the optimum results. Fuel consumption can be determined by measuring the amount of fuel consumed by the engine over a specified period.

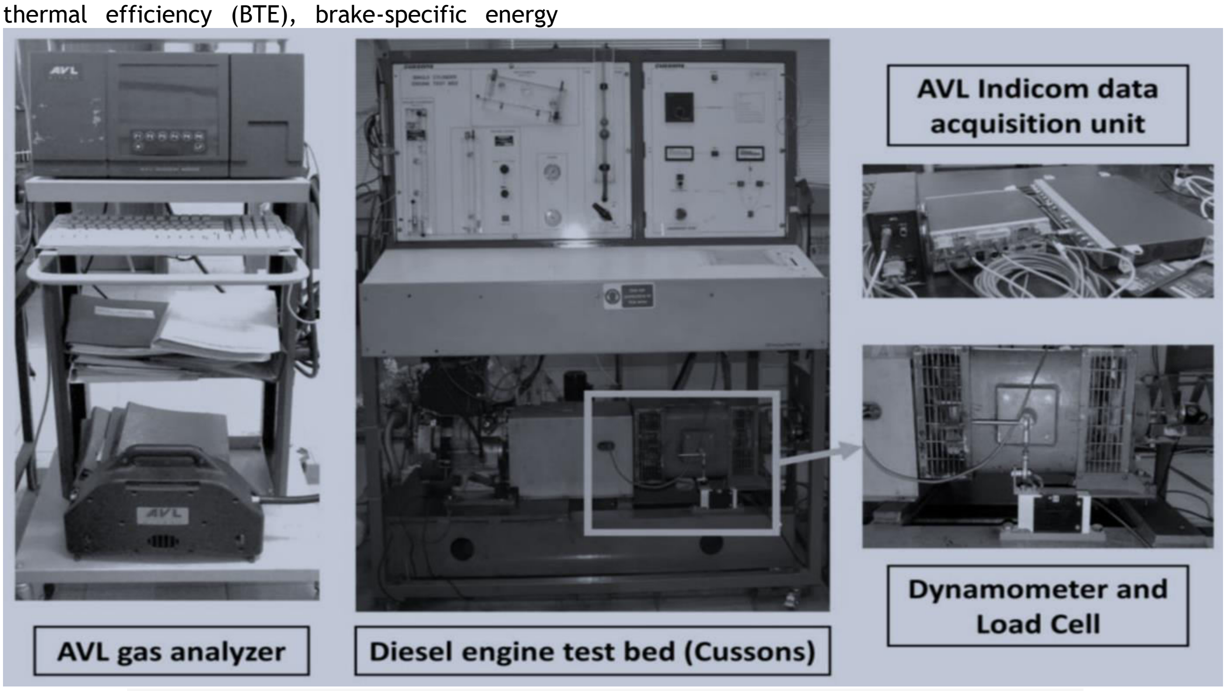


Figure 1. An experimental setup for analyzing combustion, performance, and emissions.

This can be achieved by using fuel-flow meters or by weighing the fuel before and after the test. The air/fuel ratio is monitored using exhaust gas analysis or oxygen sensors to obtain real-time data. The heat release rate is analyzed by quantifying the rate and timing of heat released during combustion. Heat-release data are obtained from the in-cylinder pressure-curve and crank-angle analysis. Utilizing advanced sensors, data-acquisition systems and control units, various engine parameters, such as temperature, pressure, fuel flowrate, and exhaust-gas composition can be continuously monitored and recorded during the engine operation. These data are essential for performance evaluation and optimization as it provides valuable information regarding the performance, efficiency, and emission behavior of diesel engines.

Combustion analysis involves studying the characteristics, behavior, and interactions of flames in combustion systems. Several experimental methods have been employed to investigate flame dynamics and gain insights into combustion processes [18]. Some commonly used experimental methods include high-speed imaging techniques, such as high-speed cameras or laser-induced fluorescence (LIF), which capture the temporal and spatial evolution of flames. They provide visual information about the flame structure, flame front propagation, and flame-stabilization mechanisms. Flame chemiluminescence analysis involves optical techniques to capture and analyze the emitted light from excited photons during combustion, providing information about the flame shape, location, and stability. Some commonly used laser diagnostics methods include laser-induced fluorescence (LIF), planar laser-induced fluorescence (PLIF), laser-induced incandescence (LII), and laser Doppler velocimetry (LDV) [16]. These techniques can provide information about species concentration, temperature, lamina flame velocity, and turbulence within the flame. Particle image velocimetry (PIV) is a technique used to measure fluid flow velocities within the flame region. By seeding the flow with particles and illuminating them with a laser sheet [13], PIV captures the motion of the particles, allowing for velocity vector mapping and the analysis of flame flow dynamics. Acoustic techniques, such as microphones or pressure sensors, are usedto analyze the sound generated by the combustion process. These measurements help in detecting and studying combustion instabilities, and can be useful for controlling and optimizing combustion systems. These experimental methods, when combined with appropriate data-acquisition systems and analysis techniques, provide valuable insights into flame dynamics, combustion performance, pollutant formation, and overall combustion-system optimization.

Quantifying the ignition-delay time is also crucial for understanding the combustion characteristics of fuels and assessing their performances in internal combustion engines. The ignition-delay time refers to the time interval between the start of fuel injection or the introduction of an ignition source and the onset of visible combustion. A constant-volume chamber alongside a rapid compression machine (RCM) or a shock tube, is typically used for ignition-delay measurements [19]. These chambers provide controlled conditions and allow for the precise measurements of the ignition-delay time.

VL FIRE is specifically designed for engine simulation and allows the detailed modeling of diesel-engine processes, including combustion, air-fuel mixing, and pollutant formation. CONVERGE is another CFD-based software that offers advanced modeling capabilities for diesel engines, including spray modeling, combustion chemistry, and emission prediction. Diesel RK [22] and Ricardo WAVE is a 1D engine-simulation software used for modeling the gas dynamics and thermodynamics of internal combustion engines. It provides tools for diesel-engine performance analysis, emissions prediction, and system-level optimization. These software packages provide a range of features and functionalities for diesel-engine analysis and simulation.

Combustion analysis involves measuring in-cylinder pressure and temperature using pressure transducers and thermocouples. These data help evaluate the combustion efficiency, peak pressure, ignition delay, and heat-release characteristics. Modelling combustion involves reaction kinetics that consist of rates of chemical reactions occurring during fuel oxidation and combustion [23]. The first step is to understand the fuel composition and the set of reactions involved, which may be obtained from existing databases, such as the GRI-Mech, AramcoMech, or CHEMKIN libraries, or developed through experimental and theoretical studies. For each reaction in the mechanism, the corresponding rate expression needs to be defined. The rate expressions incorporate temperature, pressure, and species concentrations as variables. Different types of rate expressions can be used, such as Arrhenius, Troe, or Lindemann forms, depending on the reaction kinetics and reaction mechanisms involved [23]. The various reaction parameters involved in reaction kinetics are the rate coefficients, activation energies, and pre-exponential factors. These are obtained through experimental measurements, quantum-chemical calculations, or estimated using correlations and data from similar reactions.

The developed kinetic mechanism of a reaction can be integrated into computational models, such as CFD simulations or detailed chemical kinetic solvers [24]. These models solve the conservation equations for mass, momentum, and energy along with the chemical reactions described by the kinetic mechanism. The models simulate the combustion process, including ignition, flame propagation, and pollutant formation, based on the chemistry described by the mechanism.

3. Framework to evaluate characteristics of Biofuel Blends in Gas Turbines

The research employs a multifaceted approach to evaluate the impact of biofuel blends on gas turbine performance. Experimental analyses are conducted using a gas turbine test rig to measure critical parameters such as combustion efficiency, thermal performance, and emissions profiles. Concurrently, advanced computational models are developed to simulate and predict combustion behavior under various operating conditions.

Key objectives of the study include:

1. **Fuel Composition Analysis:**
    - Investigate the chemical composition of biodiesel, bioethanol, and biokerosene to understand their inherent properties.
2. **Experimental Analyses:**
    - Conduct controlled combustion experiments on a gas turbine test rig to measure combustion efficiency, power output, and emissions characteristics for each biofuel blend.
3. **Computational Modeling:**
    - Develop detailed computational models to simulate the combustion process, validating results against experimental data to ensure accuracy.
4. **Combustion Dynamics:**
    - Explore the influence of biofuel composition on combustion stability, ignition characteristics, and flame propagation within gas turbines.
5. **Overall Efficiency Assessment:**
    - Calculate the overall efficiency of gas turbines using different biofuel blends, comparing them against traditional fossil fuels.
6. **Emissions Characterization:**
    - Analyze emissions, including nitrogen oxides (NOx), carbon monoxide (CO), unburned hydrocarbons (UHC), and particulate matter, to evaluate

the environmental impact of biofuel blends.

3.1 **Fuel Composition Analysis**

The chemical composition of biodiesel, bioethanol, and biokerosene plays a crucial role in determining their inherent properties and suitability as alternative fuels.

Biodiesel:

- **Chemical Composition:** Biodiesel is primarily composed of fatty acid methyl esters (FAME). These are produced through the transesterification reaction of triglycerides found in vegetable oils or animal fats with methanol or ethanol. Common feedstocks include soybean oil, rapeseed oil, and used cooking oil.
- **Key Properties:** Biodiesel exhibits characteristics such as high cetane number, good lubricity, and low sulfur content. It is recognized for its potential to reduce greenhouse gas emissions and dependence on fossil fuels.

b) **Bioethanol:**

- **Chemical Composition:** Bioethanol, the most common type of ethanol, is a renewable alcohol primarily derived from the fermentation of sugars found in biomass feedstocks. Common sources include corn, sugarcane, and cellulosic materials.
- **Key Properties:** Ethanol is characterized by its high octane number and oxygen content. It has a lower energy density compared to gasoline but can be blended with gasoline in various proportions. Bioethanol is known for its potential to reduce carbon dioxide emissions and enhance engine performance.

c) **Biokerosene:**

- **Chemical Composition:**Biokerosene is a renewable aviation fuel that can be derived from various feedstocks, including plant oils, algae, and waste materials. The refining processes may involve hydroprocessing or Fischer-Tropsch synthesis to produce a kerosene-like hydrocarbon.
- **Key Properties:**Biokerosene aims to mimic the properties of traditional jet fuel (kerosene) while being produced from sustainable sources. It typically has a high energy density and similar combustion characteristics, making it a promising candidate for sustainable aviation.

3.2 **Experimental Analyses**

Conducting controlled combustion experiments on a gas turbine test rig is a crucial step in assessing the performance of biofuel blends. The following steps outline the process for measuring combustion efficiency:

a) **Test Rig Preparation:**

- Ensure the gas turbine test rig is properly configured and calibrated for the specific experimental setup.
- Confirm that all instrumentation, sensors, and data acquisition systems are functional and calibrated.

b) **Fuel Preparation:**

- Prepare the biofuel blends (biodiesel, bioethanol, or biokerosene) according to the desired blending ratios and concentrations.
- Ensure that the fuel is stored and handled following safety protocols and industry standards.

c) **Baseline Measurements:**

- Run baseline tests using conventional fossil fuels to establish a reference point for comparison.
- Measure baseline combustion efficiency, temperature profiles, power output, and emissions.

d) **Biofuel Combustion Experiments:**

- Introduce the biofuel blends into the combustion chamber in the specified proportions.
- Monitor and control relevant parameters, such as fuel injection rates, air-fuel ratios, and combustion chamber temperature.

e) **Data Acquisition:**

- Continuously record data during the combustion process using sensors and data acquisition systems.
- Collect data on combustion efficiency, turbine speed, exhaust gas temperature, and emissions (NO_x, CO, UHC).

f) **Combustion Efficiency Calculation:**

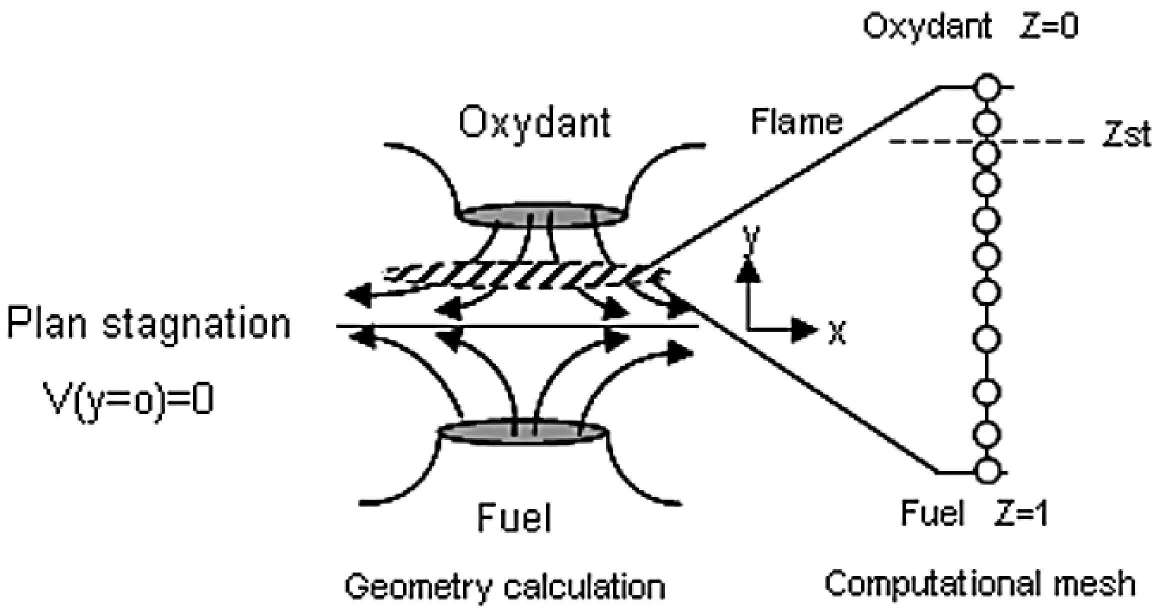
- Calculate combustion efficiency using the following formula: Combustion Efficiency (%)=(Energy OutputEnergy Input)×100Combustion Efficiency (%)=(Energy Input Energy Output)×100
- Energy output can be determined from the power output of the gas turbine, and energy input is related to the heat content of the biofuel.

g) **Repeatable Trials:**
- Conduct multiple trials for each biofuel blend to ensure repeatability and consistency of results.
- Vary operating conditions systematically to assess the impact of different parameters on combustion efficiency.

h) **Analysis and Comparison:**
- Analyze the data obtained from each experiment and compare the combustion efficiency of biofuel blends with the baseline.
- Identify trends, correlations, and potential optimizations based on the observed results.

4. Computational model

The Laminar Flamelet Model (LFM) is a combustion model commonly used in Computational Fluid Dynamics (CFD) simulations to study turbulent combustion processes. It is particularly useful for simulating combustion in conditions where the flow is turbulent but the reaction occurs in thin, laminar flame structures. Here's an overview of the Laminar Flamelet Model:



Laminar Flamelet Model (LFM):

1. **Background:**
- The Laminar Flamelet Model is based on the assumption that, within a turbulent flame, there exist thin, laminar flame structures. These structures are assumed to be thin enough compared to the flow scales, allowing for the application of simplified laminar flamelet equations.

2. **Key Concepts:**
- **Flamelet Assumption:** The model assumes that the overall flame structure can be represented by a set of precomputed, one-dimensional laminar flamelet solutions. These flamelets capture the behavior of combustion for a range of conditions.
- **Turbulence-Chemistry Interaction:** The laminar flamelet solutions are coupled with turbulence models to account for the effects of turbulence on the flame structure. Turbulent mixing is modeled by considering the interaction between the resolved flow and the flamelets.

3. **Equations:**
- **Transported Scalar Variables:** Key scalar variables, such as mixture fraction, progress variable, and enthalpy, are transported in the flow field.
- **Progress Variable:** The progress variable represents the progress of the combustion reaction. It is typically chosen to be 0 in the fresh reactants and 1 in the burned products.

4. **Process:**
- **Flamelet Library:** A flamelet library is generated through the solution of one-dimensional laminar flames at various conditions, covering the possible range of mixture fractions and progress variables.
- **Turbulence Model:** The turbulence model is used to compute the scalar dissipation rate and other turbulent quantities.
- **Flamelet Tabulation:** During the simulation, the flamelet library is interpolated to obtain the thermodynamic and transport properties at each computational cell based on the local values of mixture fraction and progress variable.

5. Conclusion

In conclusion, this study highlights the significant potential of biofuel blends as sustainable alternatives for gas turbine applications, demonstrating their ability to maintain performance while substantially reducing harmful emissions. The experimental results indicate that specific biofuel formulations can achieve comparable thermal efficiency and power output to conventional fossil fuels, effectively mitigating the environmental impact associated with traditional energy sources. Notably, the use of biofuel blends resulted in lower emissions of carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter (PM), underscoring their viability as a cleaner energy solution. These findings not only contribute to the understanding of biofuels in gas turbine operations but also emphasize the importance of integrating renewable energy sources into existing systems to promote sustainability in the energy sector. Future research should focus on long-term performance assessments and the exploration of additional biofuel formulations to further enhance combustion characteristics and emission profiles. As industries continue to prioritize environmental stewardship, the insights gained from this study will play a crucial role in advancing the adoption of biofuels in gas turbines and fostering a transition toward greener energy technologies.

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