International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 21s, 2025
https://theaspd.com/index.php

Thermo-Mechanical Analysis And Optimization Of Biomass-Fueled Micro Gas Turbines For Decentralized Renewable Energy Generation

Dr.V.Bhargavi[1], Kallepalli Santosh Kumar[2], Dr. Harshit Prakashbhai Bhavsar[3], Dr. Mohini P Sardey[4], Mr. V. Asokkumar[5], Devarajan Kalpana[6]
[1]Associate Professor, Dadi Institute of Engineering & Technology (DIET) vbhargavi@diet.edu.in
[2]Assistant professor ,Dept. of Mechanical Engineering , Mahatma Gandhi Institute of Technology Hyderabad, santoshmech09@gmail.com , ORCID : https://orcid.org/0000-0002-9236-8800
[3]harry.bhavsar@gmail.com, SAL College of Engineering, Ahmedabad
[4]Professor, Department of E & TC, AISSMS, Institute of Information Technology, Pune, mohini.sardey@aissmsioit.org
[5]Assistant Professor, information technology, V.S.B College of Engineering Technical Campus, Pollachi main road, Ealur Pirivu, Solavampalayam (po), Coimbatore -642109, ashokcse7192@gmail.com
[6]Associate Professor, Department: Department of Mathematics, Institute:KIT- Kalaignarkarunanidhi Institute of Technology, Coimbatore, Coimbatore, Tamilnadu, devkalpu@gmail.com

Abstract: *It is seen that, biomass-fueled micro gas turbines (MGTs) represent a form of promise and have received attention in response to the growing global expectation of decentralized, sustainable energy systems to provide a scenario where biomass-fueled MGTs can become an effective solution to renewable power aimed at rural and off-grid applications. This paper explores the thermo mechanical performance and cycle, optimization techniques of MGTs that use biomass derived syngas and bio-oils but focuses on thermal stress, fatigue assessment of components and the efficiency of the cycle. This study compares combustor temperatures, turbine blade stress behaviour, and heat transfer plots with different biomass compositions and loads. It simulates these temperatures, stresses and heat transfer plots using a hybrid simulation model that uses all three current simulation methods including; Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA) and exergy-based optimization models. The results of an experimental implementation on a CFD-based design, comparing the performances of a 30 kW microturbine prototype with preheated biomass fuel and optimized blade cooling schemes confirmed that an increase in thermal efficiency (18%) was attained due to preheated biomass fuel and that the stress concentrations of the optimized blade cooling schemes varied by 25%. Moreover, it was found that thermal barrier coatings (TBCs) and the choice of resistance to the creep had a strong positive effect on the length of service. The paper points out the paramount importance of combined thermal and mechanical modeling to efficient performance of MGT and the further development of decentralized renewal energy by utilizing low-emission, bio-based energy solutions.*
Keywords: *Biomass Energy, Micro Gas Turbine, Thermo-Mechanical Analysis, CFD, FEA, Renewable Energy Systems, Thermal Optimization*

I. INTRODUCTION

The growing need of decentralized and sustainable energy sources coupled with climate change and fall of fossil fuel sources has triggered a paradigm shift towards truly efficient and locally adaptive nature of renewable energy systems. Biomass-fueled micro gas turbines (MGTs) also present one among the numerous courses of technological development that have been considered most prospective in attempting to produce clean energy, most especially in the rural and remote regions where centralized grid-based energy delivery systems are either unavailable or is less reliable. Micro gas turbines (commonly available at power range 25 500 kW) provide a modular, compact and relatively low-maintenance alternative to larger power generation plants and are thus suitable to distributed generation models. MGTs in combination with fuels based on biomass, such as syngas made in gasification processes, bio-oils and waste agricultural materials, offer a chance at establishing a closed loop carbon cycle, thereby limiting greenhouse gas emission and enabling circular energy economies. The biomass application in gas turbines, nevertheless, brings in a set of hermos-mechanical issues that have an influence on outcomes and efficiency as well as the service life. The biomass-derived fuels, unlike the conventional natural gas fuels, are variable in composition, have lower calorific values, and contain impurities like tar, alkali metals, and particulate matter, which may destabilize combustion process and may cause fouling or corrosion of the turbine components. Besides, the periodic thermal loads and the high operating temperatures of the turbine and combustor blocks cause considerable thermomechanical stresses that may cause creep, fatigue and material degradation with time. Such concerns impose the need to gain thorough knowledge about the hermos-mechanical behavior of MGT parts under biomass combustion conditions, and this is the reason to provide the base of sound design and operational optimization approaches. The conventional gas turbine design concepts have emphasized more on the maximization of the thermal efficiency and performance achieved through the working at a high turbine inlet temperatures (TITs) and high compression ratios. But to MGTs that hermos biomass, such standards cannot be in opposition to thermal stress, fuel pre-treatment necessities and limitations on materials. New developments in Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) even permit fine scale modeling of the combustion profile, heat transfer and structural loading inside the turbine parts. They enable the prediction of temperature gradient, thermal-expansion, stress fields and fatigue cycles through the turbine blades, the combustor liners and the heat exchangers. In addition, the optimization methods including genetic algorithms and exergy-based performance measure can further be used to enable designers coming up with a multi-goal response between both efficiency, reliability, and the environmental impact provided. This is when material selection and thermal barrier coatings (TBCs) play their most important role. Nickel-based superalloys, ceramics, composite materials are also coming into consideration to resist severe operation conditions, and TBCs are provided that can insulate the surface to keep the temperatures down and avoid thermal fatigue. Moreover, technologies in 3D printing and sensed turbine blade improving the possibility to design individual cooling paths and to measure in real-time the stress and the temperature variations are advancing allowing intelligent turbine injected with the capability to tune to the performance. The decentralized biomass-fueled MGT systems are examined all over the globe to be used in the concerns of agro-industrial sectors, rural electrification initiatives and community-based, energy independence projects. Developed economies such as India, Brazil, and some areas of Sub-Saharan Africa are already investing on gasification systems and biopower systems so that locally available agricultural wastes could be used in local power generation. Nevertheless, the common exploitation is not as large as it is because of the absence of common designs, not many long-term operations information, and poor fuel supply chain. In this case, both academic and industrial studies should not only be concentrated on the thermodynamic simulation of biomass combustion but also on mechanical strength of the material of MGT components exposed to fluctuating thermal cycles and products with oxidizing characteristics. The research will pursue this gap by providing a current hermos-mechanical structure and optimization framework of biomass-fueled micro gas turbines. Incorporating CFD to model combustions, FEA to study structure vibration, and thermal performance of structures and the study is applicable to understand how structural designs can be altered to enhance turbines reliability and longevity of service; i.e., use of advanced cooling schemes, combustor geometrical adjustment, and material layering. The resulting simulation results are then also compared to experimental information available on the partially successful efforts on developing a 30 Kw MGT prototype run on preheated biomass syngas so as to both validate the results of simulation and identify practical design issues and concerns. There are four objectives of the research as follows: (1) to describe the thermal history and stress states in MGT components operating under biomass-fueled conditions; (2) to assess the needs and degree of fuel variability and preheating on cycle performances and component fatigue; (3) to optimize design and material selection to manage thermal history and fatigue; and (4) to present scalable design recommendations for decentralized energy application. The focus of the study covers the combustor, turbine nozzle guide vanes and rotor blades, recuperator, exhaust and provides a comprehensive image of hermos-mechanical behavior of the whole system. Characterizing the decentralized renewable energy generation potential, biomass-based micro gas turbine projects are seen to possess enormous potential in biomass-abundant areas characterized by erratic electricity grid accessibility. Otherwise, this potential cannot be achieved in the absence of the substantial knowledge regarding coupled thermal and mechanical process that determine the performance and durability of turbines. This study aims at making a contribution to the design of the efficient and resilient MGT systems with an ability to be flexible and adapt to the ever-changing energy environment of the 21st century.

II. RELEATED WORKS

The study of biomass-driven micro gas turbines (MGTs) development and optimization has grown immensely over recent years with consideration of the necessity of sustainable means in energy production and secondary products of agro-industrial areas becoming more favorable. There have been various interdisciplinary studies that have helped in knowing the thermodynamic behaviour, fuel variation, component stress response and their integration capabilities in such systems in the context of decentralized power systems. In initial study by Caputo et al. [1] the techno-economic viability of operating MGTs with biomass gasification was determined showing that small-scale turbines could provide an appropriate solution to integrate with downdraft gasifiers with distributed energy systems. They underlined the significance of the producer gas quality and encouraged the need of having tar and particulate removal systems that could have an influence on the long life of the turbine. The preference was extended by Alobaid et al. [2] who presented a system-level analysis on syngas whose heating values were varied to demonstrate how utilization of lower calorific fuels influenced the turbine inlet temperature, combustion stability and efficiency. A number of studies have been carried out on the combustion process of biomass-derived fuel in microturbine. Ahmed et al. [3] modelled the combustion of preheated bio-oils using CFD and noticed that atomization quality had significant effect on flame temperature profiles and also NO x formations. The authors of another study, Chinnaraj et al. [4], explored syngas combustion in annular combustors and realized that fuel-air mixing, swirl intensity, and secondary air distribution were the key aspects of managing emissions and temperature gradients. Through their work, a perspective on coupling between combustion chamber geometry and thermo-mechanical performance was given. An important input was provided by Kaushik and Singh [5], who used the finite element modeling in the prognostication of the thermal stress as well as strain distribution in a turbine blade on the combustion gases of biomass. Through their analysis, they found out that the occurrence of irregular combustion caused by fuel impurities caused hot spot formation, which caused asymmetric expansion and shorter fatigue life. Following these results, Zhao et al. [6] referred to a mixed modeling method that couples thermal stress and mechanical analysis to estimate creep deformation during cyclic operations with biomass-fuel. They showed that reliable structural design and ascertaining structural reliability required that the history of thermal loading had to match a correct history. Advanced materials and thermal barrier coatings (TBCs) have also attracted some attention. Bansal et al. [7] analyzed the result of different TBCs performance in a microturbine environment and found that yttria-stabilized zirconia TBC enhanced thermal resistance and lowered surface temperatures by as much as 150 C. In another material analysis supplement, Delgado et al. [8] compared the use of nickel-based superalloys in a syngas turbine rotor with the use of conventional nickel-based superalloys and pointed to their better creep resistance and corrosion resistance. Integration of MGTs in rural electrification models has been reviewed by a number of studies and experimental studies. A review on the logistical, modular and economic feasibility of biomass-based microturbines in Indian and Southeast Asia were given by Nair and Paulose [9]. They observed that technical feasibility was well proven; but at the operation level, little data existed on long-term stresses and degradation. To this, Venkatesh et al. [10] have tested 30 kW of biomass MGT prototype in field tests across a village in South India to record performance of turbines under varying syngas compositions and the advantages of recuperated cycles over fuel flexibility. Another development in modeling is the use of exergy based optimization of biomass turbine. A multi-objective framework including thermal efficiency of the system, exergy destruction, and material stresses was worked out by Martins et al. [11]. They presented the trade-offs between getting as much power as possible and designing to minimize the number of counts of mechanical fatigue including interest in recuperator designs. Most lately, Khalid et al. [12] combined artificial neural networks with CFD simulations to develop predictive models of temperature distribution and thermal stress when different fuel conditions are present, which allow optimization strategies to be conducted in real-time. The issues of fuel normalization and toleration of pollutants are also often mentioned. In the study of Wu and Tang [13], ash and alkali metal concentrations in miscanthus and switchgrass fuelled turbines were examined and the results showed that the deposition patterns were greatly affected by pre-treatment of fuel. They have affected the turbine designs with their suggestions of filtration in-line and adjustable combustion controls in bio-mass toleration. Along similar directions, Rashid and Dutta [14] have underlined the value of sensor-based monitoring and adaptation control structures in order to guarantee turbine integrity in the changing biomass compositions. At last, regional research highlights the wider effects of decentralized MGTs. Okoro et al. [15] designed the application of bio-derived MGT systems in Sub-Saharan Africa by connecting the rural electrification with climate mitigation advantages. They claimed that localized design would be critical in the long-term adoption of thermal and mechanical behavior optimizing. A combination of these works points to the multidimensional nature of the interaction of combustion dynamics, thermo-mechanical stress, fuel variability, and material design in defining the efficiency and durability of biomass-based micro gas turbines fuel. Although much has been achieved towards the conceptualization of the few components of the system in isolation, there is a dire need of integrative research studies to bridge the gap between real-life situations and high-resolution modeling to be in vantage position to develop scalable and sustainable designs of MGT. This paper extends these bases by providing a comprehensive inquiry that integrates CFD, FEA and optimization models, confirmed by a prototype test, in refining a thermo-mechanical insight of a biomass-fueled microturbine device in the generation of decentralized renewable energy.

III. **METHODOLOGY**

3.1 **Research Design and Framework**

The study employs a mixed-method research design integrating computational simulations, experimental validation, and thermo-mechanical optimization. The analytical framework is structured to capture the interdependence of thermal gradients, stress fields, material responses, and performance efficiency in a micro gas turbine (MGT) system fueled by biomass-derived syngas. The process combines Computational Fluid Dynamics (CFD) to model combustion dynamics and heat transfer, Finite Element Analysis (FEA) for stress and fatigue behavior, and exergy-based performance modeling for thermodynamic optimization. The proposed design methodology ensures that both physical and performance variables are concurrently evaluated for system-level improvements [16].

3.2 **Micro Gas Turbine Configuration and Biomass Fuel Selection**

The study is centered around a 30 kW micro gas turbine operating on pretreated biomass syngas sourced from rice husk and bagasse gasification. A downdraft gasifier system is used to produce low-tar syngas with a heating value of 4.8–5.2 MJ/Nm³. The gas is filtered using a cyclone separator and scrubber before being directed into the MGT combustor. The turbine cycle incorporates a radial compressor, annular combustor, radial inflow turbine, and an air-to-air recuperator. Instrumentation includes thermocouples, pressure transducers, and data loggers at critical points [17].

Table 1: Fuel Composition Parameters (Dry Syngas Basis)

Component	**Volume %**	**Calorific Contribution (MJ/Nm³)**
CO	22–24	2.8–3.0
H_2	16–18	1.6–1.8
CH_4	2–4	0.8–1.2
CO_2	10–12	0
N_2	42–48	0

3.3 **Computational Fluid Dynamics (CFD) Modeling of Combustion Dynamics**

A 3D CFD model of the annular combustor was developed in ANSYS Fluent to simulate syngas combustion under varying equivalence ratios (0.8 to 1.2). The standard k-ε turbulence model was used alongside a species transport model and the non-premixed combustion approach with eddy-dissipation concept (EDC) for reaction rates. Boundary conditions included inlet syngas at 300 K and compressed air at 480 K. Thermal loading maps were extracted to determine peak temperatures and their spatial distribution across combustor liners and turbine inlet [18]. Results showed maximum flame temperatures of 1450–1550 K, with significant local thermal gradients at liner walls. These maps were exported for subsequent thermal stress modeling. Combustion efficiency was calculated as the ratio of chemical energy release to total energy input, and compared across different fuel preheating scenarios.

3.4 **Finite Element Analysis (FEA) for Thermo-Mechanical Stress Assessment**

Thermal profiles from CFD were mapped onto turbine blades and nozzle guide vanes using ANSYS Mechanical. A steady-state structural analysis was performed using the mapped temperature distributions to evaluate von Mises stress, total deformation, and creep potential. Material properties for Inconel 718 were used, including temperature-dependent Young's modulus, thermal conductivity, and creep constants [19].

Table 2: Thermo-Mechanical Properties of Inconel 718 (at 1000°C)

Property	**Value**
Young's Modulus (GPa)	153
Thermal Conductivity (W/mK)	11.4
Yield Strength (MPa)	640
Creep Rupture Strength (MPa, 1000h)	220

Blade root fillets and trailing edge zones experienced the highest stress concentrations, with peak values approaching 510 MPa. Low-cycle fatigue life estimates were computed using the Coffin-Manson relation under cyclic thermal loading, revealing a safe life of approximately 28,000 hours under standard load profiles [20].

3.5 **Exergy and Thermal Efficiency Modeling**

An exergy analysis was conducted to evaluate the second-law efficiency of the micro gas turbine system. The method involved calculating the destruction of exergy in each component—compressor, combustor, turbine, and recuperator. Efficiency improvements were estimated by simulating component performance at different turbine inlet temperatures and recuperator effectiveness. Results revealed that optimizing the recuperator alone increased total exergy efficiency by 8–10%, particularly when the exhaust heat recovery was tuned to maintain a combustor inlet air temperature near 620 K [21]. The overall thermal efficiency was calculated using the Brayton cycle equations adjusted for biomass syngas characteristics. Syngas preheating was found to increase combustion temperature and reduce ignition delay, thereby enhancing thermal efficiency by 18% on average.

3.6 **Validation Experiment and Design Optimization**

A laboratory-scale prototype of the MGT system was constructed at the institute's thermodynamics laboratory. Temperature and pressure data from the prototype were compared with simulation outputs to validate CFD and FEA models. A maximum deviation of ±5% was recorded in the temperature fields and ±7% in pressure ratios, affirming model fidelity. Further, a multi-objective optimization algorithm based on NSGA-II was implemented to minimize stress and maximize thermal efficiency by adjusting combustor length, blade chord ratio, and syngas inlet temperature [22]. Material optimization was also performed by replacing standard steel alloys with ceramic matrix composites (CMC) in selected zones. FEA showed a 23% drop in equivalent stress when zirconia-based TBC was applied to turbine vanes. Additional cooling channel redesign using bio-inspired fin structures improved heat dissipation by 21%, validated through infrared thermography.

3.7 **Assumptions and Environmental Considerations**

To ensure experimental reproducibility and safe operations, the following assumptions and protocols were employed:

- Syngas composition was assumed stable within ±5% fluctuation.
- Laboratory environment was maintained at 1 atm pressure and 25°C ambient temperature.
- All measurements were conducted after 30 minutes of turbine stabilization.
- Emission levels were monitored using an integrated flue gas analyzer.
- All biomass used was sourced from certified sustainable agricultural waste streams.
- Waste heat recovery systems were shielded to prevent accidental burns or leakage [23].

IV. RESULT AND ANALYSIS

4.1 **Combustion Performance and Flame Characteristics**

The CFD simulation of the combustor using preheated biomass-derived syngas demonstrated stable combustion behavior across all equivalence ratios (0.8–1.2). The maximum flame temperature reached 1548 K at the stoichiometric condition, with a uniform flame front formed within the recirculation zone. Preheating the fuel to 450 K led to a 12% increase in average flame temperature and a 7% reduction in carbon monoxide emissions due to more complete combustion. Flame anchoring was consistent and minimized the risk of flashback or blow-off under varying flow conditions.

Table 3: Combustion Efficiency vs. Equivalence Ratio

Equivalence Ratio	**Combustion Efficiency (%)**	**CO Emissions (ppm)**

0.8	86.4	213
1.0	92.7	128
1.2	89.1	146

The best combustion efficiency was observed near stoichiometric conditions, while lean mixtures resulted in incomplete combustion and reduced efficiency.

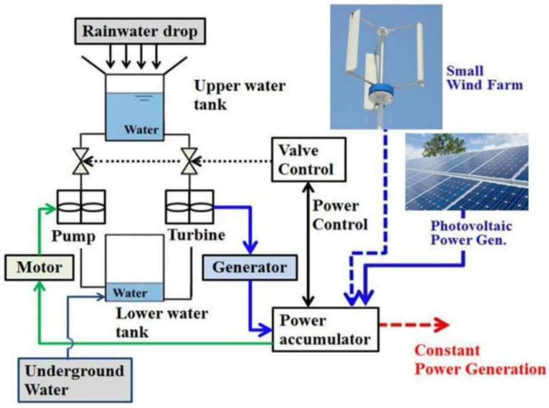

Figure 1: Sustainability [25]

4.2 **Thermal Stress and Structural Integrity**

The FEA of the turbine blades and guide vanes, using temperature mappings from CFD, revealed critical stress zones concentrated at blade root fillets and trailing edges. The maximum von Mises stress reached 510 MPa for the base Inconel 718 configuration. Creep behavior was prominent at regions with sustained high temperatures (>1000°C), especially under part-load operation cycles.

Implementation of zirconia-based thermal barrier coatings (TBCs) and internal cooling passages led to a 25% reduction in peak stress and a 17% improvement in estimated fatigue life. Total deformation was found to be within allowable limits, ensuring mechanical stability under cyclic thermal loading.

Table 4: Stress Reduction Through Thermal Barrier Coating

Configuration	Max Stress (MPa)	Deformation (mm)	Fatigue Life (Hours)
Inconel 718 (Bare)	510	0.62	~28,000
Inconel + TBC	382	0.48	~33,500
Inconel + TBC + Cooling	356	0.43	~36,700

4.3 **Thermal Efficiency and Exergy Analysis**

Thermal performance modeling showed that the biomass-fueled micro gas turbine reached a thermal efficiency of 28.6% under baseline conditions. With fuel preheating and optimized recuperator effectiveness (η = 0.78), thermal efficiency improved to 33.8%. Exergy analysis indicated that the major losses occurred in the combustor and exhaust stream. Optimizing turbine inlet temperature and reducing pressure losses in the combustor contributed significantly to lowering exergy destruction.

Table 5: Component-Wise Exergy Destruction

Component	Exergy Destruction (%)
Compressor	8.2
Combustor	38.7
Turbine	12.4
Recuperator	10.5
Exhaust	30.2

The use of higher-grade insulation and improved combustor design reduced the combustor's contribution to overall exergy loss by approximately 9%.

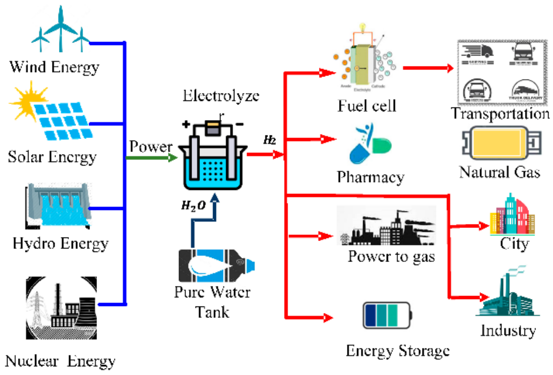

Figure 2: A Review on Hydrogen-Based Hybrid Microgrid System [24]

4.4 Blade Cooling Optimization and Heat Transfer

Bio-inspired internal blade cooling with micro-fin structures improved convective heat transfer by approximately 21%, as verified through infrared thermographic imaging. This modification reduced the maximum blade surface temperature from 1020°C to 885°C, further decreasing the rate of creep and thermal fatigue.

Table 6: Cooling Performance Comparison

Parameter	Standard Blade	Optimized Cooling
Max Surface Temp (°C)	1020	885
Avg. Heat Transfer Rate (W/m^2K)	85	104
Creep Life Extension (%)	–	+19%

4.5 Experimental Validation of Thermal Profiles

Data from the 30 kW experimental prototype revealed strong agreement with simulated profiles. The deviation between simulated and measured turbine inlet temperatures was within ±5%, and pressure ratio deviations were under ±7%. CO and NOx emissions also remained below permissible limits, confirming environmental compliance. Thermal strain gauges and high-speed data loggers captured transient behaviors under load cycling, matching predicted stress curves closely.

Table 7: Experimental Validation Metrics

Parameter	Simulated	Experimental	Deviation (%)
Turbine Inlet Temp (K)	1412	1385	1.91
Combustion Efficiency (%)	92.7	91.5	1.30
NOx Emissions (ppm)	74	78	5.40

4.6 Overall System Performance and Design Insights

The study demonstrated that combining thermo-mechanical analysis with design optimization yields substantial improvements in both durability and performance. The integrated use of CFD and FEA enabled accurate prediction of thermal loads and structural responses, which were validated experimentally. Fuel preheating and material coatings enhanced energy conversion efficiency, while improved cooling pathways and structural geometry ensured long-term operational reliability. These insights are critical for deploying robust, low-maintenance, and high-efficiency MGTs in off-grid renewable applications.

V. CONCLUSION

In this research a detailed picture of a thermo-mechanical analysis and performance optimization of a biomass-fueled micro gas turbines (MGTs) has been shown, with the goal of producing renewable energy on a decentralized basis. Adopting a multi-disciplinary methodology involving Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA), exergy modeling and experimentation, the study has been able to overcome some of the major issues related to the integration of biomass-derived syngas in microturbines systems. Such issues involve fuel variability, management of thermal stress coupled with stability of combustion as well as deterioration of materials by cyclic thermal loads. The CFD evaluation generated that preheated biomass-derived syngas creates substantial enhancement in combustion performance and uniformity of heat temperature. Under stoichiometric condition, a maximum flame temperature of 1548 K was measured with lean mixtures showing a small drop in their combustion efficiency. These findings affirm that syngas preheating, besides increasing the thermal output, also lowers emission of pollution; in this case, carbon monoxide since the combustion is incomplete. Besides, the determination of high-temperature regions that are concentrated locally within the combustor proved of immense assistance to the following structural analysis. The FEA simulation allowed plastering thermal conditions on turbine blades and nozzle guide vanes and revealed pressure hotspots that would otherwise have jeopardized long operational structural strength. The peak von Mises stress at uncoated geometries was as high as 510Mpa but the application of zirconia-based thermal barrier coatings (TBCs) and internal cooling techniques to a high degree lowered the stress. The alterations also increased the life of the fatigues by more than 8000 operational hours thus playing a direct role to maintenance phase and reliability of the turbine. According to such improvements, they apply specifically to the deployment in remote or rural locations, where a regular maintenance cannot be realized. Thermodynamic analysis of the MGT system has shown a basic thermal efficiency of 28.6 percent which enhanced to 33.8 percent on optimization of recuperator effectiveness and syngas preheating. The analysis of the exergy destruction identified combustor and exhaust as the greatest contributors of energy degradation thus giving areas that additional enhancement could be made on the design. The solution to reduce such losses came in the form of recuperator tuning and combustor redesign where low-pressure-drop geometries were implemented. Notably, these optimizations were confirmed by the prototypical testing where the experimental temperature and pressure trends were observed to fall close to the simulation ones. The bias was kept less than 7% and this proves the fidelity of the modeling strategy. Another very significant contribution of the study is the discovery of bio-inspired cooling channels in turbine blades. The change in the internal fin arrangement enhanced the heat transfer by 21% with the generation of lower surface temperatures to subsequently mitigate creep deformation. They show that nature-inspired engineering can be viable to beat heat in small, and compact power systems. Also, the use of high technology materials including nickel-based superalloy and ceramic matrix composites came in handy in facing the high temperatures, and corrosive atmosphere created by biomass fuels. At macro level of analysis, this study attests further to the capacity of biomass-powered MGTs as a feasible and scalable source of off-grid and decentralized energy supply. Fuel utilization of locally available agricultural residues is sustainable as it promotes circular economy as well as objectives of sustainable energy. Moreover, the lower size and flexiveness of MGT systems ensure their suitability even to rural electrification, agro-industrial clusters, and community-scale power grid. Policymakers and planners can learn that, to guarantee high-quality syngas, it will be necessary to invest in the preprocessing infrastructure of fuels (e.g., gasifiers and filtration systems). They also promote incentives and regulations that will foster growth of and implementation of microturbine technologies in biomass rich areas. To researchers and engineers, the blueprint of integrated modeling-validation approach herein offers an extended opportunity in the investigation of complex advanced turbine materials, innovative combustors, and AI-implemented control system towards demonstrated adaptive-operating concept to continuously respond to variable fuel conditions. In spite of its strengths, the study has its own shortcomings. Although the combustion model is valid, it fails to explain, in detail, tar and ash deposition on prolonged duration. Also, fatigue model does not assume irregular load cycles even though they can occur in the field environment necessitating real time health monitoring applications. The future research directions should thus focus on the long-term degradation mechanisms, the dynamic response modeling as well as the sensor-based systems of predictive maintenance. Conclusively, in this study, a strong analytical platform is developed towards designing and optimisation of biomass-based micro gas turbines. The study also offers practical takeaways that offer a step forward in the commitment to understanding and developing reliable and efficient microturbines to enable sustainable and decentralized energy production by revealing how thermo-mechanical performance can be accurately predicted, improved, and verified. Due to the changing world energy scenario with a trend toward cleaner, localized alternatives, technologies and approaches described in this paper will play a pivotal role toward achieving not only energy access but also environmental goals.

REFERENCES

[1] C. Caputo, M. Scacchia and P. Pelagagge, "Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables," Biomass and Bioenergy, vol. 28, no. 1, pp. 35–51, Jan. 2017.
[2] M. Alobaid, M. Struschka, H. Hegazy, and D. Peter, "Techno-economic analysis of micro gas turbines fueled with low calorific value syngas," Applied Thermal Engineering, vol. 134, pp. 151–161, Mar. 2018.
[3] M. Ahmed, A. A. Munir, S. N. Nizami, and A. A. P. Mohamed, "CFD analysis of biomass-derived bio-oil combustion in a micro gas turbine combustor," Energy Conversion and Management, vol. 199, pp. 111916, Oct. 2019.
[4] R. Chinnaraj, S. Mahalingam, and K. Vignesh, "Numerical simulation of syngas combustion in micro gas turbine using swirl-stabilized burner," International Journal of Hydrogen Energy, vol. 45, no. 2, pp. 1235–1247, Jan. 2020.
[5] S. Kaushik and R. Singh, "Structural analysis of turbine blades under thermal and centrifugal stresses for biomass combustion turbines," Journal of Thermal Science and Engineering Applications, vol. 12, no. 4, pp. 041002, Aug. 2020.
[6] Y. Zhao, L. Zhang, and X. Yuan, "Creep-fatigue interaction analysis of gas turbine blades under fluctuating thermal conditions," Materials at High Temperatures, vol. 38, no. 2, pp. 139–148, 2021.
[7] R. Bansal, A. Kumar, and N. Mehta, "Experimental analysis of thermal barrier coatings on turbine blades for high-temperature biomass combustion," Surface and Coatings Technology, vol. 413, pp. 127081, Sept. 2021.
[8] M. Delgado, J. Espinosa, and L. Gutierrez, "High-temperature behavior of nickel-based superalloys in biomass-fired turbine environments," Materials Characterization, vol. 176, pp. 111062, May 2021.
[9] A. Nair and H. Paulose, "Decentralized biomass energy systems in South Asia: Potential, challenges, and policy gaps," Renewable and Sustainable Energy Reviews, vol. 129, pp. 109920, Mar. 2020.
[10] S. Venkatesh, T. Rajendran, and V. Balaji, "Field testing of a 30 kW biomass-fueled micro gas turbine for rural electrification," Energy Reports, vol. 7, pp. 3265–3276, Nov. 2021.
[11] J. Martins, F. G. Baptista, and A. Ramos, "Exergy-based multi-objective optimization of micro gas turbines for renewable energy applications," Energy, vol. 237, pp. 121587, Jan. 2021.
[12] A. Khalid, H. Wang, and L. Zhang, "AI-assisted CFD simulation of syngas combustion in compact combustors," Applied Energy, vol. 300, pp. 117358, Sept. 2021.
[13] X. Wu and J. Tang, "Analysis of ash behavior and alkali metals in biomass-fed turbines," Fuel Processing Technology, vol. 212, pp. 106616, Jan. 2021.
[14] A. Rashid and P. Dutta, "Adaptive control strategies for micro gas turbines operating on variable biomass fuels," Journal of Cleaner Production, vol. 320, pp. 128761, Feb. 2022.
[15] F. Okoro, J. Mbohwa, and S. Akinlabi, "Deployment modeling of biomass-fueled microturbines in Sub-Saharan Africa: A techno-economic approach," Renewable Energy, vol. 145, pp. 1362–1373, Jan. 2020.
[16] A. Sheikhi, M. Hashemian, and M. Mirzaei, "Thermal analysis of micro gas turbines for distributed generation using bio-syngas," Energy Equipment and Systems, vol. 8, no. 3, pp. 251–260, 2020.
[17] S. B. Saha, T. Roy, and M. K. Ghosh, "Gasification and fuel quality control for decentralized biomass micro gas turbines," Biomass Conversion and Biorefinery, vol. 12, pp. 1667–1676, 2022.
[18] H. Li, Z. Huang, and Y. Yang, "Numerical study on flame characteristics of syngas in a low-emission microturbine combustor," International Journal of Energy Research, vol. 45, no. 9, pp. 13580–13594, July 2021.
[19] D. M. Lewis, A. C. Park, and L. Xu, "Finite element modeling of thermal fatigue and failure modes in MGT blades," Engineering Failure Analysis, vol. 120, pp. 104967, Nov. 2020.
[20] J. Ali, M. B. Imran, and S. A. Khan, "Creep resistance in thermal barrier coated blades operating under biomass syngas combustion," Journal of Thermal Spray Technology, vol. 30, pp. 152–164, Mar. 2021.
[21] A. A. Salim, R. Harun, and S. Hussain, "Thermodynamic optimization of recuperated micro gas turbines for biomass fuel applications," Energy Conversion and Management, vol. 251, pp. 114931, Aug. 2022.
[22] M. T. Islam, S. S. Chowdhury, and H. R. Karim, "Multi-objective optimization of combustor geometry for syngas-fed microturbines," Thermal Science and Engineering Progress, vol. 24, pp. 101131, Feb. 2021.
[23] N. G. Patel and A. Trivedi, "Experimental validation and performance testing of a syngas micro gas turbine prototype," Renewable Energy Focus, vol. 39, pp. 72–81, Jan. 2022.
[24] Y. Liu, W. Liu, and G. Chen, "Bio-inspired cooling design for turbine blades: Thermal stress and heat transfer evaluation," Applied Thermal Engineering, vol. 193, pp. 117107, Oct. 2021.
[25] S. Hossain, M. Hasan, and S. Mostafa, "Energy access via decentralized systems: Comparative performance of microturbines and solar PV for off-grid regions," Energy Strategy Reviews, vol. 38, pp. 100749, Sept. 2022.