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Development and Exergo-Economic Analysis of a Gasifier Cookstove with Thermoelectric System

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ABSTRACT

This study presents the development and exergo-economic analysis of a biomass gasifier cookstove integrated with a thermoelectric generator (TEG) for generating electricity from waste heat. The design utilizes biomass as a fuel source, converting it into combustible gases through gasification while capturing waste heat for electricity generation using a TEG. The thermoelectric system powers a fan to improve combustion efficiency. Experimental results show stove efficiencies between 76% and 82%, and the exergo-economic analysis reveals a cost-effective design with high exergy utilization. This dual-purpose system demonstrates potential for improving energy efficiency and access to electricity in developing regions.

Keywords: gasifier, cookstove, exergo-economic

INTRODUCTION

Energy access and environmental sustainability are critical challenges facing developing countries, particularly in rural areas where traditional biomass cookstoves are still widely used(*Lv et al.*, 2014). These stoves are inefficient, emit harmful pollutants, and contribute to deforestation and carbon emissions. The World Health Organization(RS et al., 2015) estimates that exposure to household air pollution from traditional cooking practices causes millions of premature deaths annually.

Renewable energy technologies, including thermoelectric generators (TEGs), offer innovative solutions for energy recovery from waste heat(Al-Shetwi, 2022; Chendake et al., 2014). TEGs can convert heat from combustion processes into electricity, potentially improving the efficiency of biomass stoves while generating power for household use. This paper presents the development of an improved biomass gasifier cookstove integrated with a TEG. The system addresses both the energy efficiency of cooking and electricity generation in off-grid communities, providing a clean energy alternative07:17 PM.

The study also includes an exergo-economic analysis(Oyedepo et al., 2014), which combines exergy analysis with economic considerations to evaluate system performance and cost-effectiveness. This integrated approach enables an assessment of the potential for scaling up the technology in developing regions.

LITERATURE REVIEW

Thermoelectric Generators (TEGs)

TEGs are semiconductor devices that convert temperature differences directly into electrical power using the Seebeck effect(*Yahya et al.*, 2020). The principle is based on the generation of a voltage when there is a

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temperature gradient across the material. TEGs as illustrated in fig. 1 have been used in various applications, including waste heat recovery from automotive exhaust systems and industrial processes(Majumdar, 2004). Their advantages include no moving parts, quiet operation, and the ability to operate in extreme conditions. However, the efficiency of TEGs remains relatively low, requiring optimization in integration with energy systems like cookstoves(Huang et al., 2012).

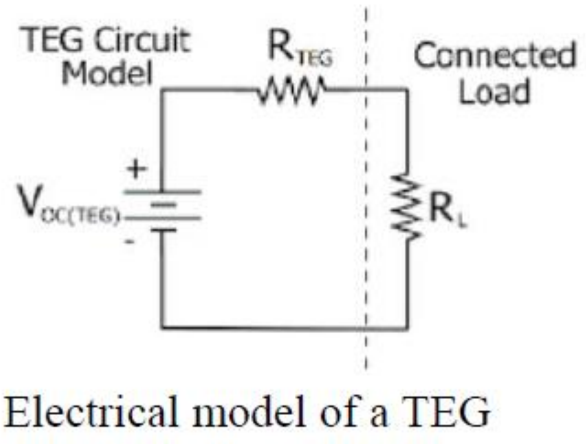

Fig. 1

Biomass Gasification

Biomass gasification is the process of converting solid biomass into combustible gases, such as carbon monoxide, hydrogen, and methane, through partial oxidation at high temperatures. This process occurs in a gasifier(Antonova & Looman, 2005; Belonio, 2005; Lv et al., 2014; Lv et al., 2016), which can be configured in several ways, including updraft and downdraft designs. Gasification is considered a cleaner alternative to direct combustion, as it allows for more efficient fuel use and reduced emissions. The gasification process can also be integrated with TEGs to recover heat for electricity generation.

Exergo-Economic Analysis

Exergo-economic analysis combines exergy (a thermodynamic measure of energy quality) with economic considerations to assess the cost-effectiveness of energy systems. Exergy analysis focuses on the useful work that can be extracted from a system, accounting for inefficiencies and energy losses(Oyedepo et al., 2014; Panwar et al., 2023). By integrating economic factors such as investment and operational costs, exergo-economic analysis provides a comprehensive evaluation of system performance(Situmorang et al., 2020).

METHODOLOGY

Stove Design and Construction

The gasifier cookstove developed in this study consists of two primary phases: pre-combustion, where solid biomass is converted into gaseous fuels, and combustion, where these gases are fully combusted. The stove features a cylindrical reactor with primary and secondary air intakes, powered by a fan connected to a thermoelectric generator. The primary air intake facilitates gasification, while the secondary intake ensures complete combustion of the produced gases.

To improve the efficiency of the stove, glass wool insulation is used to reduce heat loss, and the TEG is integrated on the stove’s surface to capture waste heat. The electricity generated by the TEG powers the fan, which enhances combustion by increasing airflow through the stove.

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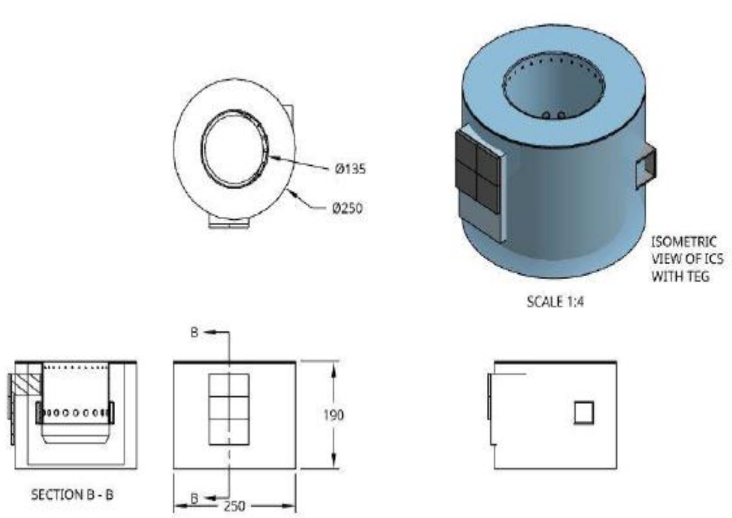

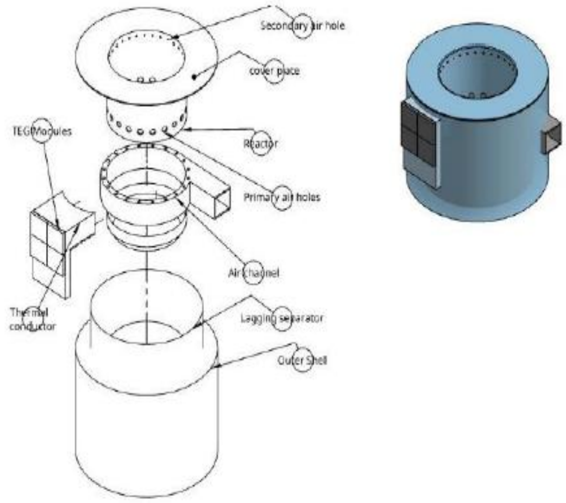

Fig. 2a Orthographic view of the Improved cookstove   2b. Exploded view of designed Improved cookstove

Performance Testing

The stove's performance was evaluated using a water boiling test (WBT) (Chendake et al., 2014)with different types of biomass, including wood, charcoal, rice husk, and cow dung. The test measured the time and fuel required to boil water, and the stove's efficiency was calculated based on the energy input and heat output. The TEG was tested for voltage, current, and power output across a range of temperature differences.

Exergo-Economic Analysis

The exergy efficiency of the system was calculated using the ratio of useful energy output to total energy input. Economic analysis was performed by calculating the capital costs of the stove components and the operating costs of the system. The exergo-economic factor, representing the portion of the total cost attributed to inefficiencies in the system, was also determined.

RESULTS

Stove Efficiency

The stove demonstrated high efficiency in converting biomass into useful heat, with results ranging from 76% to 82%, depending on the type of biomass used. Charcoal exhibited the highest efficiency due to its higher calorific value, while rice husk showed the lowest efficiency due to its higher moisture content.

The mass of biomass required to bring 1 liter of water to a boil varied between 0.013 kg and 0.034 kg, depending on the fuel type. The stove's design, particularly the use of a forced draft fan, significantly improved combustion efficiency. This experiment was repeated for other fuel sources and recorded in Table I below.

Table I: Results for Rate of Fuel Combustion calculation

Biomass	**Stoichiometric Air (SA)**	**Rate of Fuel Combustion (RFC)KgHr^{-1}**	**Specific Energy (Es) MJ/Kg**
Wood	7.1	2	16
charcoal	6	2.9	24
Rice Husk	6.97	3.4	13
Cow dung	13.97	5.23	18

Table II: Results of water boiling test

Fuel	Mass of Fuel (Kg)	T_f - T_i (ºK)	C_v (KJ/Kg)	Efficiency (%)
Wood	0.23	70.1	19000	76
charcoal	0.13	71.8	29600	82
Rice Husk	0.34	70.02	12296.19	79.3
Cow dung	0.32	69.98	13201.78	78.4

The results in Table II show the water boiling test which indicate that the stove requires very little quantity of fuel to bring the water to boil and the efficiency is between 76 to 82%. The calorific value of the fuel also contributes to the efficiency of the stove in that the higher calorific value fuels generate more heat hence boil the water faster.

Electricity Generation

The TEG generated up to 1.75 W of power, with charcoal providing the highest voltage and power output due to its high combustion temperature. The integration of the TEG with the cookstove proved effective, providing enough power to sustain the fan and generate surplus electricity for lighting or charging devices. Table III show that the voltage, current and Power recorded from the panel with the highest value of temperature difference for the various fuels used. It also follows that the biomass with higher calorific value produces the highest voltage difference hence power

Table III: Results of TEG power experiment at maximum temperature difference for various biomass

Fuel	T_f - T_i (ºC)	Voltage (V)	Current (A)	Power
Wood	183	2.3	0.5	1.15
charcoal	191	2.5	0.7	1.75
Rice Husk	150	1.7	0.15	0.25
Cow Dung	142	1.3	0.12	0.15

Exergo-Economic Analysis

The exergo-economic analysis revealed that the stove had a high exergo-economic factor of 97%, indicating that most of the investment cost contributed to useful work. The exergy destruction cost was calculated to be only 0.2% of the total investment, demonstrating the system’s efficiency. The total capital investment for the stove was ₦35, 300, with minimal operational costs due to the self-sustaining nature of the fan powered by the TEG.

DISCUSSION

The integration of a thermoelectric generator with a gasifier cookstove offers a dual benefit: efficient cooking and electricity generation. The high stove efficiency and low biomass consumption make it a suitable solution for households in off-grid areas. The exergo-economic analysis confirms that the system is cost-effective, with a high return on investment due to its energy-saving potential and the additional benefit of electricity generation.

The results suggest that with appropriate scaling, this technology could significantly reduce reliance on traditional fuels, improve energy access, and mitigate environmental impacts. However, further research is needed to optimize TEG performance and reduce production costs, making the technology more accessible to low-income households.

CONCLUSION

This study demonstrates the potential of a gasifier cookstove integrated with a thermoelectric generator for improving energy efficiency and access to electricity in developing regions. The stove’s high efficiency and cost-effectiveness, as shown by the exergo-economic analysis, make it a promising solution for sustainable cooking and power generation. Future work should focus on further optimizing the design and exploring large-scale implementation.

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