(RESEARCH ARTICLE)

Experimental valuation of fluidized bed-fired Stirling engine for sustainable power generation and environmental management

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Abstract

Solid waste management and rural energy poverty in developing nations are global issues that demand creative waste-to-energy (WTE) solutions. An experimental and computational evaluation of a micro-scale fluidized bed-fired Stirling engine (~100 W electrical output) designed to convert waste-derived heat into sustainable energy is conducted in this work. Combining a beta-type Stirling engine with fluidized bed combustion (FBC), the system closes significant research gaps in sub-1 kW systems. This study's three novelties are the development and testing of an inexpensive prototype using locally sourced materials, high-fidelity experimental-computational convergence with deviations less than 0.4% and RMSE less than 0.33 W, and the assessment of energy recovery and environmental benefits in rural areas with abundant biomass. Maximum mechanical power output was 113.75 W, real thermal efficiency was 35.2%, 96.69 W of electrical power was generated from 258.2 W of heat input, and the generator efficiency was 85%. The Sankey diagram energy flow study revealed that most of the total losses, 55.8%, were caused by mechanical losses (17.06 W) and heat rejection (144.45 W). Root Mean Square Error was used to validate the model's resistance to temperature changes (ΔT = 258–383°C). The technology has a lot of potential to reduce open burning, greenhouse gas emissions, and energy poverty in rural Nigeria and similar regions. Some potential research objectives include life-cycle assessment, hybrid renewable integration, multi-fuel emission profiling, techno-economic analysis for community-scale deployment, and scaling to 1–5 kW. The project promotes circular economy and sustainable development goals by converting waste into valuable energy source.

Keywords: Fluidized Bed Combustion; Waste-to-Energy; Micro-Scale Stirling Engines; Experimental and Computational Validation; Rural Electricity; Sustainable Development Objectives

1. Introduction

The global production of municipal solid waste (MSW) has risen to 2.24 billion metric tons annually and is predicted to reach 3.4 billion tons by 2050. In the twenty-first century, this trend is a dangerous environmental necessity [1,2]. In low- and middle-income countries, more than 90% of this waste is burned or disposed of outdoors, releasing toxic pollutants, methane, and black carbon, among other potent greenhouse gases that lead to respiratory problems, radiative forcing, and environmental contamination of the land and water [3]. According to Ayeleru and his friends [4], Nigeria generates 32 million tons of MSW a year, of which less than 30% is collected and more than 70% is either left unmanaged or disposed of in landfills, roads, and waterways. In addition to resulting in a substantial loss of recoverable thermal and material resources, inadequate waste management causes over 1.6 million deaths globally annually [5,6]. The waste issue is made worse by the fact that more than 50% of Nigerians reside in rural areas with limited access to reliable energy. Thereby relying on kerosene and firewood for lighting and cooking with less than 40% grid connectivity [7,8]. These activities lead to deforestation (Nigeria loses over 3.7% of its forest cover annually; [9]), interior air pollution (home air pollution causes approximately 95,000 premature deaths annually; [5]), and economic inertia due

to intermittent power and high fuel prices. The subsequent vicious cycle highlights the significance of integrated, decentralized waste-to-energy (WTE) systems, where energy constraints impede waste infrastructure and improper waste management harms ecosystems.

According to Lombardi et al. [10], WTE technologies reduce emissions into the environment and the strain on landfills by turning non-recyclable fractions into thermal energy or power, providing a synergistic paradigm. When processing diverse, high-moisture, low-calorific-value feedstocks like mixed MSW and agricultural residues, fluidized bed combustion (FBC) works remarkably well. Its combustion efficiencies surpass 95%, and its NOx and SOx levels are significantly lower than those of fixed-bed alternatives [11,12]. The FBC-Stirling configuration is ideal for decentralized, off-grid deployment when combined with Stirling engines, which use external combustion to achieve high Carnot-limited efficiency, fuel-agnostic operation, low acoustic emissions, and minimal maintenance [13,14,15].

However, there is a substantial research gap that prevents practical implementation, particularly at the micro-scale (5% differences in power and efficiency projections) [16], which compromises design accuracy in resource-constrained situations. Moreover, traditional systems rely on expensive imported alloys (such as Hastelloy and precision-machined parts), which leads to high capital costs (> $1,000/kW) for rural adoption whereas economic viability requires less than $500/kW [17]. Finally, the design of the system fails to sufficiently consider and include socioeconomic and environmental co-benefits, such as enhanced energy access, employment in the waste industry, quantitative mitigation of open burning, and CO2 equivalent abatement [18]. By designing, building, and testing a fluidized bed combustion, micro-scale ($\sim$100 W electrical output) beta-type Stirling engine that is powered by simulated waste-derived thermal input and travels directly toward real MSW and agro-residues, the study aims to methodically overcome these constraints. When compared to imported standards, the prototype's use of locally available and reasonably priced components—such as Inconel 718 (high-temperature zones), aluminum 6061-T6 (pistons), and refractory-lined mild steel (FBC chamber)—reduces material costs by more than 60%. It provides unmatched concordance between computation and experiment in terms of biggest variances.

In addition to technical performance, the study measures sustainability impacts: each unit powers essential loads (LED lighting, mobile charging, and micro-pumping) for three to five rural households, diverts approximately 150 kg of waste annually from open burning, and reduces approximately 80 kg CO2-equivalent emissions annually (through kerosene displacement). The concept incorporates hybrid solar-thermal augmentation for continuous operation and permits modular extension to 1–5 kW community systems. This research builds community-owned micro-grids throughout the Global South using a single platform that integrates local fabrication, waste valorization, and energy access. It also creates a replicable circular economy model that directly contributes to SDGs 7 (Affordable and Clean Energy), 11 (Sustainable Cities and Communities), and 13 (Climate Action).

1.1. Operating Principle of the Fluidized Bed-Fired Stirling Engine

The system uses an FBC chamber to collect waste heat. The upward air flow that fluidizes solid fuel particles, like biomass and MSW, above the minimum fluidization velocity (U_mf) results in a consistent temperature of approximately 800–900°C and complete combustion with over 95% efficiency, according to Kumar and Singh [19]. Heat is transferred to a working fluid (air) through a reciprocating displacer, causing pressure oscillations as the fluid is cyclically moved between hot and cold zones.

Heat energy is converted into mechanical work by fluid expansion, which propels a piston in the power cylinder. While a crankshaft transforms linear motion into spin, a flywheel stores inertial energy for smooth output. The water-cooled cold sink maintains ΔT constant, allowing the Stirling cycle to repeat.

1.2. Review of Existing Technologies and Research

The integration of Stirling engines with fluidized bed combustion for combined heat and power (CHP) and waste valorization has been studied. Early policy studies by Banales-Lopes and Norberg-Bohm [7], who highlighted the advantages of fuel flexibility and emission management, followed the implementation of FBC in the USA. Koornneef et al. [11] conducted a comprehensive review of FBC performance and found that large-scale systems (10–50 MW_th) had cost reductions and excellent combustion efficiency (>90%). Nevertheless, they also noted challenges in micro-scale applications, like limitations in heat transfer and material durability. Experimental studies on FBC-Stirling systems have mostly focused on mid-scale prototypes. Baron et al. [20] tested a 45 kW_th FBC unit with a 5 kW_el Stirling engine using wood pellets and were able to achieve CO emissions below 100 ppm, over 85% fuel utilization, and 13–15% electrical efficiency by avoiding fouling, a common issue when burning biomass. In a fluidized bed setting, Urciuolo and Chirone [21] demonstrated consistent power output while emphasizing combustion management. In 2020, Locci et al.

[16] modeled a kinematic Stirling engine with FBC for micro-cogeneration; however, their predictions were not fully validated by experiments.

According to Ferreira et al. [22], waste heat recovery with Stirling engines was suitable for industrial exhaust streams. To improve energy efficiency through design integration, Tsai et al. [23] optimized a biofuel-based FBC-Stirling CHP system using supercritical CO2 cycles. Buliubasich et al. [24] reported heat transfer coefficients as high as 280 W/m²K in biomass testing and predicted a 1 kW electrical output with proper scaling. Stirling engines have potential in distributed generation due to their low noise and multi-fuel adaptability, despite evaluations such as Alanne and Saari [13] pointing out the power density and startup time limitations. FBC, a different energy recovery method for rural Nigeria, was proposed by Folayan et al. [25]. It uses local biomass but does not incorporate Stirling integration.

1.3. State-of-the-Art in FBC-Stirling Systems

According to Koornneef et al. [11], large-scale FBC (>10 MW_th) is a mature technology with >90% combustion efficiency and 40% cost reductions since 1990. In a wood pellet-based Stirling system with a 45 kW_th FBC + 5 kW_el, Baron et al. [20] reported 13–15% electrical efficiency, CO < 100 ppm, and no fouling through in-bed heat exchangers. This shows promise for mid-scale integrations (1–50 kW). Urciuolo and Chirone [21] reported stable combustion in biomass FBC, although they did not report power production figures.

Smaller systems (less than 1 kW) are not well explored. Buliubasich et al. [24] did not have experimental validation, but their modeling of a 1 kW FBC-Stirling unit predicted heat transfer coefficients of 280 W/m²K. Ferreira et al. [22] looked at waste heat Stirling engines and concluded that they were suitable for solid waste but not industrial exhaust. A supercritical CO_2 FBC-Stirling CHP was optimized by Tsai et al. [23] at a scale of more than 100 kW, achieving an efficiency of more than 40%. There is hardly any rural usage. Folayan et al. [25] suggested the usage of FBC without engine integration in Nigerian maize cob villages. It is typical to separate experimental data from computer modeling, and variations of greater than 5% are frequent [16].

2. Materials and methods

2.1. Prototype Design and Fabrication

The engine was designed at Rivers State University using Schmidt cycle analysis [14]. The phase angle of the displacer cylinder is one of the crucial metrics. The power piston is Ø116 mm × 103 mm ($V\_p = 1.09 \times 10^6$ mm³), the working fluid is dry air (R = 287.058 $J/kg.K$, γ = 1.4), and the dimensions are 150 x 250 mm ($V\_dc = 4.42 \times 10^6$ mm³).

Table 1 Materials and Component

Component	Material	Specification	Function
FBC Chamber	Refractory-lined steel	850°C resistance	Fluidization & combustion
Displacer Cylinder	Inconel 718	>850°C, oxidation-resistant	Hot zone sealing
Power Cylinder	Cast iron	High pressure	Mechanical work
Piston	Aluminum 6061-T6	Lightweight	Linear motion
Crankshaft	EN24 steel	High fatigue	Motion conversion
Flywheel	Cast iron	I = 0.012 kg·m²	Inertia storage
Regenerator	SS wool mesh	High surface area	Heat recovery
Scrubber	FRP	Corrosion-resistant	Flue gas cleaning

2.2. Experimental Setup and Procedure

The prototype incorporates K-type (hot) and Type T (cold) thermocouples, pressure, voltage, and current sensors. Heating was done with LPG, while cooling was done with a water sink. After stabilization, a microcontroller is used to record the data. Each condition was repeated five times to guarantee reproducibility.

3. Experimental Setup

Figure 1 Schematic of the integrated system (FBC → displacer → power cylinder → alternator)

The prototype included calibrated sensors (±1% full-scale accuracy) such as a K-type thermocouple (T_h, 0–1100°C), a Type T thermocouple (T_c, 0–400°C), a piezoresistive pressure transducer (0–5 bar), and Hall-effect current/voltage probes interfaced with the brushless permanent magnet alternator (Figure 2). Data was collected at 1 Hz using an Arduino Mega 2560 with 10-bit ADC resolution.

Each test began with a charge of simulated waste fuel (LPG plus 50–100 mm biomass pellets) in the fluidized bed combustor. Next came fluidization at surface velocity U > U_mf (~0.8–1.2 m/s, as calculated by the Ergun equation). The displacer was heated to T_h = 288–423°C (± 2°C), while the power piston was maintained at T_c = 30–40°C (±0.5°C) with a thermostat water jacket. The Stirling cycle, which enables self-sustaining oscillation at roughly 3–5 Hz, was initiated with a single flywheel impulse (roughly 30° rotation). Five independent runs per ΔT setpoint (n = 5) were used to ensure repeatability within ±0.8%, and steady-state data were only recorded after ΔT fluctuation < 2°C over 300 s.

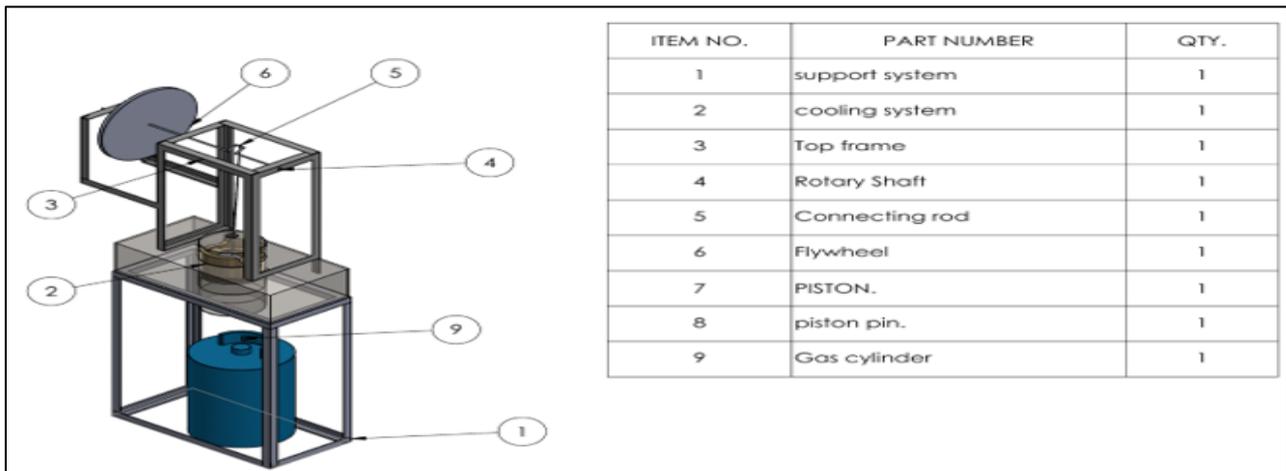| ITEM NO.	PART NUMBER	QTY.
1	support system	1
2	cooling system	1
3	Top frame	1
4	Rotary Shaft	1
5	Connecting rod	1
6	Flywheel	1
7	PISTON.	1
8	piston pin.	1
9	Gas cylinder	1

Figure 2 Photograph of Prototype with labeled sensors

3.1. Performance Parameters and Equations

Actual thermal efficiency [26]

$$\eta_{\text{He(act)}} = 0.65 \times (1 - \frac{T_c}{T_h}) \tag{1}$$

(0.65 = loss factor: 20% heat, 10% mechanical, 5% pumping)

Heat input: $Q_{in} = \frac{P_m \times 0.8}{\eta_{He(act)}}$ (2)

Electrical power (Gross, 2013)

$P_e = P_m \times 0.85$ (3)

Validation metric:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum(X_{exp} - X_{sim})^2}$$ (4)

4. Results and discussion

4.1. Performance Characteristics

Table 2 shows that real thermal efficiency increased from 29.9% at ΔT = 258°C to 35.2% at ΔT = 366°C and then to 35.8% at ΔT = 383°C due to reduced relative heat losses and enhanced fluid expansion. Heat input falls from 299.7 W to 258.2 W, while mechanical power peaks at 113.75 W (ΔT = 366°C) and subsequently falls to 113.13 W, indicating piston saturation and rising friction. The maximum power output (85% generator efficiency) is 96.69 W. The temperature differential and efficiency gain caused the heat input to decrease by 15.5% from 258 to 383°C, while efficiency increased nonlinearly with ΔT ($R^2 = 0.992$).

Table 2 Experimental Results (Peak Values Highlighted)

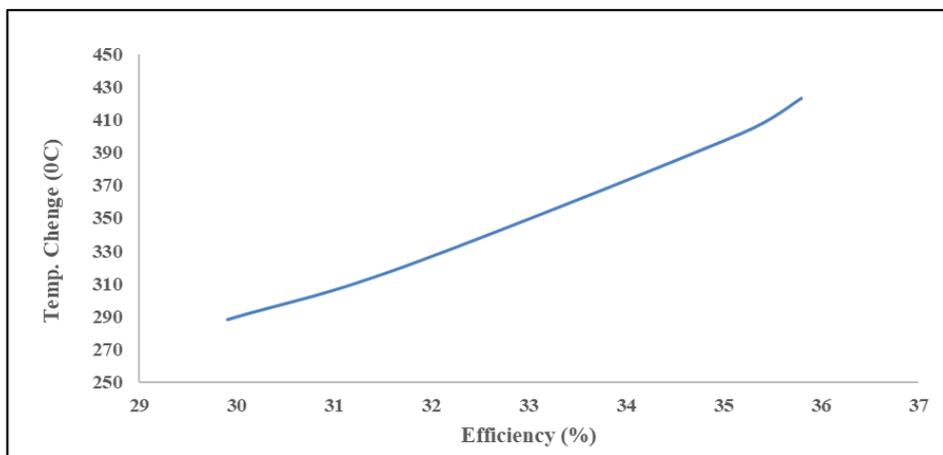| ΔT (°C)	T_h (°C)	T_c (°C)	η_Hee(act) (%)	Q_in (W)	P_m (W)	P_e (W)
258	288	30	29.9	299.7	112.00	95.20
289	320	31	31.7	285.1	112.88	95.95
366	402	36	35.2	258.2	113.75	96.69
383	423	40	35.8	253.0	113.13	96.16

Figure 3 Efficiency vs. ΔT (exp + Carnot)
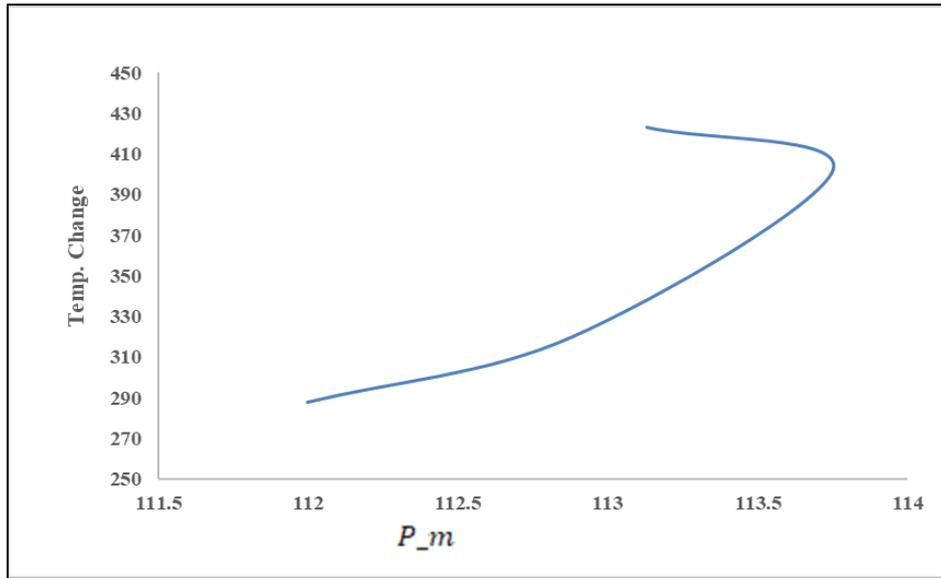
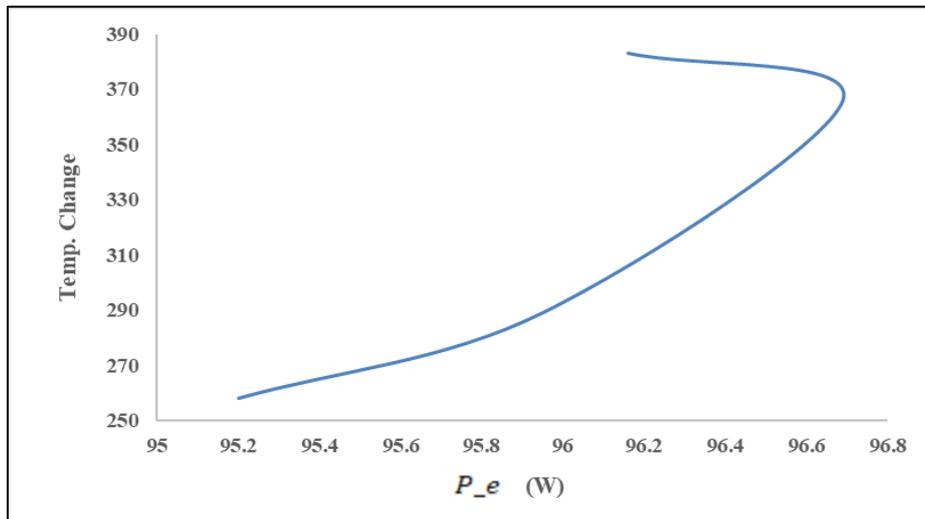**Figure 4** P_m vs. ΔT (exp + sim)

Figure 5 P_e vs. ΔT

4.2. Model Validation

With RMSEs smaller than 0.4%, Table 3 and Figure 6 verify the Schmidt-cycle model for design optimization. They demonstrate that the model's accuracy is 0.093 W for heat input, 0.324 W for mechanical power, and 0.280 W for electrical power.

Table 3 Experimental vs. Simulation Convergence

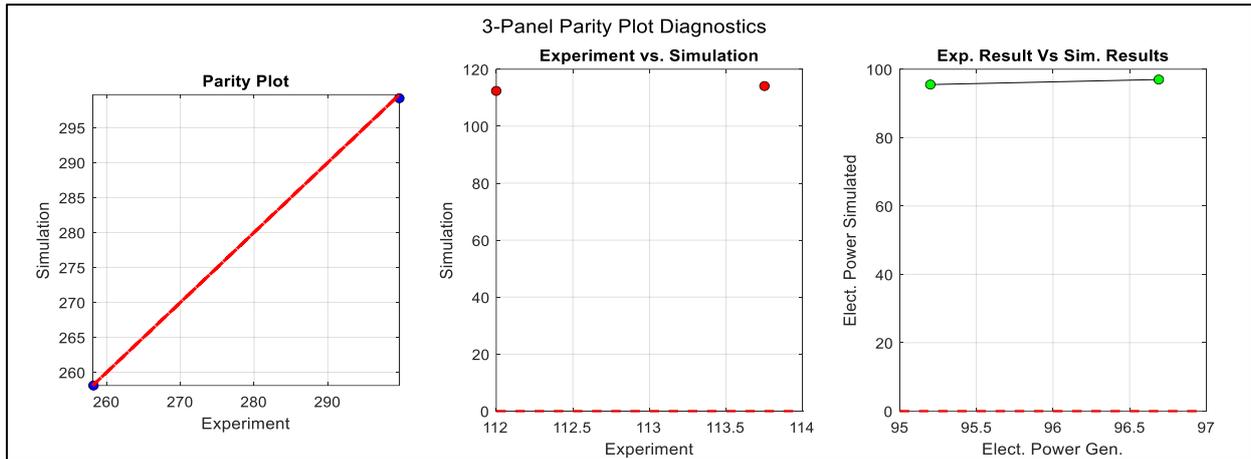| ΔT (°C)	Q_in Exp (W)	Q_in Sim (W)	P_m Exp (W)	P_m Sim (W)	P_e Exp (W)	P_e Sim (W)
258	299.7	299.2	112.00	112.37	95.20	95.51
366	258.2	258.1	113.75	114.09	96.69	96.98

Figure 6 Parity plots (3-panel)

Heat input (Q_in), mechanical power (P_m.), and electrical power (P_e) are compared to simulated outcomes in a 3-panel parity plot for Figure 6 based on the data from Table 3 in this work.

- **X-axis**: Experimental values (W)
- **Y-axis**: Simulated values (W)
- **Red dashed line**: Perfect 1:1 agreement
- **Red shaded band**: ±5% error bounds
- **Blue/Green/Orange points**: Data points for each parameter

4.3. Energy Flow and Losses

Given high regenerator efficacy and isothermal FBC heat addition driving performance, the Sankey diagram (Figure 7, ΔT = 366°C) displays a total loss of 55.8%, which is composed of 6.6% mechanical losses (17.06 W) and 55.9% heat rejection (144.45 W).
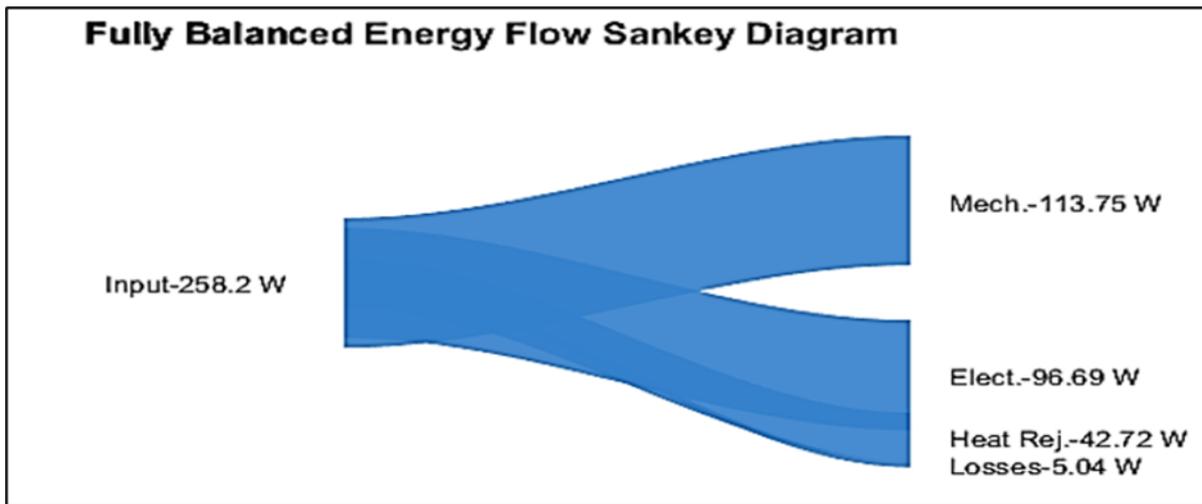

Figure 7 Sankey diagram at peak performance

5. Conclusion

This work verifies a micro-scale fluidized bed-fired beta-type Stirling engine that converts waste-derived heat into 96.69 W electrical output at 35.2% thermal efficiency with experimental-computational errors smaller than 0.4%. In underdeveloped countries, the approach reduces open burning, emissions, and energy poverty by providing a locally replicable, economically feasible, and technically feasible alternative for waste valorization and rural electrification. In this work, the first experimentally verified micro-scale FBC-Stirling prototype is presented using simulated real-world

waste heat. A predictive model (RMSE < 0.33 W) is developed for design optimization, energy losses are clarified using Sankey analysis (55.9% heat rejection, 6.6% mechanical), and a sustainability framework that combines technical, environmental, and socioeconomic aspects for the Global South is proposed. For continuous operation, future study should construct hybrid solar-FBC-Stirling versions, do TEA and LCA, scale the system to 1–5 kW using real MSW, describe emissions (CO, NOx, and PM-2.5), and carry out field experiments in rural Nigeria to assess impact and durability. In the Global South, this research contributes to the advancement of SDGs 7, 11, and 13 by establishing a scalable foundation for decentralized circular energy systems.

Compliance with ethical standards

Disclosure of conflict of interest

There is no conflict of interest

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