



Thermal Performance Modeling and Calibration of an Improved Cookstove with Integrated Thermal Energy Storage

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Abstract

In Nigeria, where access to reliable cooking energy is challenging, improving the efficiency of traditional cookstoves is important for reducing fuel consumption and mitigating environmental impacts. This study was motivated by the need to develop a predictive model for an improved cookstove incorporating thermal energy storage (TES) to enhance thermal performance and extend cooking capability. By integrating experimental data from Water Boiling Tests with computational modeling, this research develops and calibrates a MATLAB-based simulation of heat transfer processes in a multi-layered cookstove design. The model incorporates detailed geometry of combustion chamber, air gap, granite rock TES, and fiberglass insulation layers, implementing energy balance equations to predict temperature profiles, fuel consumption, and efficiency metrics. Calibration against experimental data yielded close alignment, with simulated overall final efficiency of 12.6% compared to experimental 26.3%, boil time of 36.8 minutes compared to experimental boil time of 57.9 minutes, and fuel consumption of 0.905 kg identical to measured values. The energy distribution analysis revealed that about 35% of fuel energy contributed to water heating, about 50% remained stored in TES, while the remainder represented system losses. Comparative analysis with conventional charcoal stoves shows the improved TES design achieves Tier 3 low-power specific consumption (0.023 MJ/min/L), outperforming most conventional stoves in simmering efficiency. These findings demonstrate the model's capability to predict cookstove performance while identifying opportunities for efficiency improvement through design optimization. This research contributes to the development of computational tools for cookstove design optimization, offering a path for enhanced energy efficiency in household cooking applications.

Keywords: Improved Cookstove, Thermal Energy Storage (TES), MATLAB Simulation, Heat Transfer Modeling, Energy Efficiency, Water Boiling Test, Solid Fuels, Biomass Energy.

1.0 Introduction

This study aims to develop and calibrate a MATLAB-based simulation model for predicting the thermal performance of an improved cookstove with integrated thermal energy storage (TES). The research focuses on modeling heat transfer processes through multiple stove layers, calibrating the model with experimental Water Boiling Test (WBT) data, and analyzing energy distribution to identify optimization opportunities for enhanced cooking efficiency.

Household cooking in Nigeria and similar developing contexts relies on a spectrum of fuel types spanning the "energy ladder" from traditional solid biomass (wood, charcoal), through liquid fuels (kerosene), to gaseous fuels (LPG, natural gas) and electricity. Each fuel type presents distinct trade-offs in availability, cost, convenience, and environmental impact. Adegbola et al (2021) also reported the growing high cost of hydrocarbon fuel sources and the need for the development of a dual energy source that uses both electricity and gas for cooking.

Traditional biomass cookstoves remain widespread in Nigerian households and other emerging economies, particularly in rural areas where access to modern cooking fuels is limited. Das et al (2024) in an experimental study, concluded that demand for biomass energy has skyrocketed because of the exponential population growth, resulting in voluminous quantities of wood being used. These stoves typically exhibit low thermal efficiencies and high emissions, contributing to deforestation and indoor air pollution. Improved cookstoves with TES have emerged as promising solutions for solid fuel applications, capturing excess heat during high-power operation for use during low-power cooking or subsequent cooking cycles. The main advantage of Improved cookstoves over traditional stoves is the use of insulating materials like clay, high density rock materials or fiber glass to retain heat and increase the efficiency of the cookstove.

Many studies have explored cookstove design improvements across different fuel types and stove designs, with recent focus on integrating TES materials in solid fuel stoves as well as inclusion of thermo-

electric generator (TEG) modules into stoves to power a fan for clean combustion. MacCarty *et al.* (2010) documented performance variations across stove designs, highlighting efficiency ranges from 15% to 40% depending on design parameters. Similarly, Jetter *et al.* (2012) emphasized the importance of standardized testing protocols, particularly the Water Boiling Test, for comparative performance assessment across fuel types. More recently, Kumar *et al.* (2020) investigated phase change materials for thermal storage in cookstoves, demonstrating efficiency improvements of 5-15% over conventional designs. Comparative studies such as Bantu *et al.* (2018) have shown that improved designs with heat retention features can significantly outperform traditional stoves in both efficiency and emissions. Dekhare *et al.* (2024) optimized the design and performance of a cookstove by simulating performance over grate height, pot gap and secondary hole diameter against targeted response parameters of flame temperature, thermal efficiency and combustion efficiency. The achieved thermal efficiency complied with standards for natural draft cookstoves, classifying it as a Tier 2 cookstove. In their research findings, Kaputo *et al.* (2024) showed that the improved multipurpose cooker stove consumed 0.3643 kg/L less fuel compared to traditional stoves. This fuel savings not only reduces the cost of raw materials but also contributes to environmental sustainability by lowering deforestation rates and air pollution. Hassan *et al.* (2017) investigated the emission and performance of an existing Improved cookstove model with a proposed model through CFD modelling of the combustion and heat transfer.

The study showed that the use of secondary air and reduced dimension of the combustion chamber geometry is a very convenient way of reducing emissions and improving the heat transfer. Through the results, the proposed cookstove was found to be better in terms of emission and performance level. In improving the energy performance of stoves, Adihou *et al.* (2021) modified the grid and primary air flow of a Nansu stove, its performance was compared to a corresponding reference stove and an ordinary Nansu stove by carrying out a controlled cooking test. The results of these tests show that the modified Nansu is significantly more economical, in terms of fuel consumption and cooking time, compared to the ordinary Nansu stove. The savings made by the modified Nansu stove compared to the ordinary Nansu stove are 34.57% to 64.31% in specific consumption and 9.42% to 37.81% in cooking time depending on the type of dish. Okino *et al.* (2021) in their research used CFD to study the performance of cookstoves with insulation. The results showed that heat was concentrated on the inside of the combustion chamber due to perfect insulation of the stove with sawdust as temperatures decreased toward the wall of the stove. The heat flux generated indicated that the thickness of insulation layer of the stove can be 6 cm or less while the stove would still remain hot with thermal efficiency reaching 35.5% at cold start. Darlami *et al.* (2020) studied and optimized the effects of fuel feeding rate, chimney height, opening area of air fuel inlet, inlet area of interconnecting tunnel, combustion chamber height, grate height and insulating material on thermal efficiency of improved cookstove. Thermal efficiency of modified cookstove increased from 18% to 25.6% by optimizing the operating parameters. In the experimental study by Patil *et al.* (2013), an energy balance to assess the causes of heat losses and reduced thermal efficiencies in Indian stoves was carried out. The results showed that allowance for the secondary air aids in combustion of volatiles and improves thermal efficiency approximately by 4%. Gogoi & Baruah (2016) developed a steady state heat transfer model to predict performance of biomass stove with varying operating and design conditions. Model is validated for a commercial stove for test conditions as 24% thermal efficiency and 17 mins minimum boiling time. The model is expected to be useful for new design, assessment of existing design and performance evaluation of biomass stove.

Despite these advancements, predictive modeling of cookstove thermal performance remains underdeveloped, particularly for designs incorporating TES. Existing models often oversimplify heat transfer processes or lack experimental validation (Tryner *et al.*, 2014). This gap limits designers' ability to optimize stove parameters before physical prototyping, increasing development costs and time. Furthermore, comparative analysis between improved and conventional designs is often lacking in modeling studies, making it difficult to quantify potential benefits.

This study attempts to address these limitations by developing a MATLAB simulation that models heat transfer through all stove layers, implements dynamic energy balance equations, and validates predictions against experimental WBT data. The model accounts for combustion chamber geometry, air gap thermal resistance, granite rock TES properties, insulation effectiveness, and pot-water heat transfer dynamics. By calibrating simulation parameters with experimental measurements and comparing performance against conventional stoves, the research provides a validated tool for predicting cookstove performance and guiding design improvements.

The findings contribute to the growing body of knowledge on clean cooking technologies by demonstrating how computational modeling can accelerate stove optimization, reduce development costs, and ultimately enhance adoption of efficient cooking solutions in Nigerian households. Through comparative analysis, this work also identifies the specific advantages of TES-integrated designs over conventional alternatives.

2.0 Materials and Method

2.1 Stove Design and Experimental Data

The study focuses on an improved cookstove design incorporating thermal energy storage, with detailed geometry derived from technical specifications. The multi-layered construction includes:

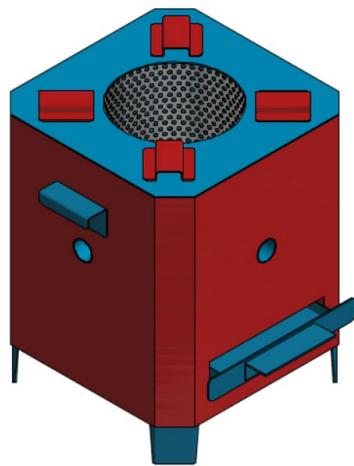


Figure 1a: Isometric Drawing of Stove

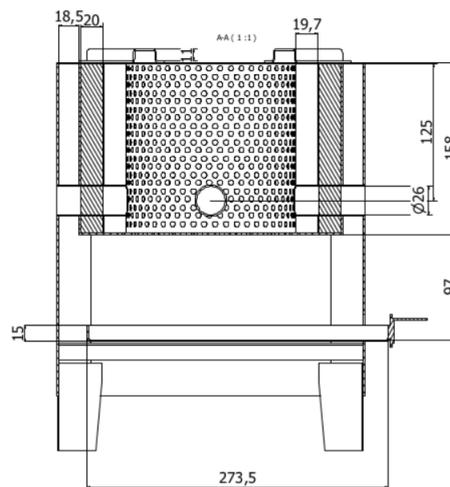


Fig 1b: Cross section of Stove

1. **Combustion Chamber:** Cylindrical mild steel chamber (145 mm diameter × 158 mm height, 2.25 mm thickness)
2. **Air Gap:** 19.7 mm annular space surrounding combustion chamber
3. **TES Layer:** 20 mm thick compacted granite rock pebbles
4. **Insulation:** 18.5 mm thick fiberglass layer
5. **External Casing:** Rectangular mild steel casing (280 mm × 280 mm)
6. **Pot Gap:** 12 mm clearance between stove top and cooking pot

Experimental data for model calibration was obtained from Water Boiling Tests conducted following ISO IWA protocols (ISO, 2012). Three replicate tests were performed to ensure statistical validity. Key performance metrics included:

- High Power Thermal Efficiency: 26.3% (average of three tests)
- Time to Boil: 57.9 minutes (average)
- Fuel Consumption: 0.905 kg charcoal (average)
- Water Mass: 2.5 kg initial, with evaporation during boiling
- Low Power Specific Consumption: 0.023 MJ/min/L (average)

2.2 Comparative Framework

To contextualize the performance of the improved TES cookstove, a comparative analysis was conducted against conventional charcoal stoves using the ISO IWA tier system. Performance data for six conventional charcoal stoves and one LPG stove were obtained from laboratory testing reports. The IWA system evaluates stoves across tiers 0-4 in four key areas: fuel efficiency, emissions (CO and PM_{2.5}), and safety, with Tier 4 representing the highest performance level.

2.3 Mathematical Model Development

A MATLAB simulation model was developed based on fundamental heat transfer principles and energy conservation laws. The model implements a thermal network approach with five temperature nodes representing key stove components: combustion gases (simplified as heat input), air gap, TES, cooking pot, and water.

2.3.1 Energy Balance Equations

The core model is built on the first law of thermodynamics, implementing energy conservation for each component:

Overall System Energy Balance:

matlab

$$dE_{\text{system}}/dt = Q_{\text{combustion}} - Q_{\text{water}} - Q_{\text{losses}} - Q_{\text{stored}}$$

Fuel Energy Input:

matlab

$$Q_{\text{fuel}} = \dot{m}_{\text{fuel}} \times \text{LHV}_{\text{fuel}}$$

Where $\dot{m}_{\text{fuel}} = 0.000260$ kg/s (calibrated burn rate) and $\text{LHV}_{\text{fuel}} = 29.8 \times 10^6$ J/kg for charcoal.

2.3.2 Heat Transfer Formulations

Convective Heat Transfer:

matlab

$$Q_{\text{conv}} = h \times A \times \Delta T$$

Conductive Heat Transfer through Layers:

matlab

$$Q_{\text{cond}} = (k \times A \times \Delta T) / L$$

Radiative Heat Transfer (neglected in this model but acknowledged as a limitation):

matlab

$$Q_{\text{rad}} = \epsilon \times \sigma \times A \times (T_1^4 - T_2^4)$$

2.3.3 Governing Differential Equations

TES Temperature Dynamics:

matlab

$$dT_{\text{TES}}/dt = (Q_{\text{combustion_TES}} - Q_{\text{TES_pot}} - Q_{\text{TES_loss}}) / (m_{\text{TES}} \times c_{p_TES})$$

Pot Temperature Dynamics:

matlab

$$dT_{\text{pot}}/dt = (Q_{\text{TES_pot}} - Q_{\text{pot_water}}) / (m_{\text{pot}} \times c_{p_pot})$$

Water Temperature Dynamics:

- **Sensible heating phase** ($T < 100^\circ\text{C}$):

matlab

$$dT_{\text{water}}/dt = Q_{\text{pot_water}} / (m_{\text{water}} \times c_{p_water})$$

- **Boiling phase** ($T = 100^\circ\text{C}$):

matlab

$$dm_{\text{water}}/dt = -0.00005 \text{ kg/s (evaporation rate)}$$

2.3.4 Geometric Calculations

Radial dimensions were calculated from the stove specifications:

matlab

$$r_{\text{combustion}} = 0.0725 \text{ m}$$

$$r_{\text{air_gap}} = 0.0922 \text{ m (} r_{\text{combustion}} + \text{air_gap_thickness)}$$

$$r_{\text{TES}} = 0.1122 \text{ m (} r_{\text{air_gap}} + \text{TES_thickness)}$$

$$r_{\text{outer}} = 0.1307 \text{ m (} r_{\text{TES}} + \text{insulation_thickness)}$$

Volume calculations:

matlab

$$\text{Combustion_volume} = \pi \times r_{\text{combustion}}^2 \times 0.15$$

$$\text{Air_gap_volume} = \pi \times (r_{\text{air_gap}}^2 - r_{\text{combustion}}^2) \times 0.15$$

$$\text{TES_volume} = \pi \times (r_{\text{TES}}^2 - r_{\text{air_gap}}^2) \times 0.15$$

$$\text{TES_mass} = \text{TES_density} \times \text{TES_volume} \times 0.7 \text{ (70\% packing factor)}$$

2.4 Simulation Parameters and Calibration

The simulation was implemented with the parameters shown in Table 1:

Table 1: Simulation parameters and material properties

Parameter	Value	Unit	Description
Simulation time	5000	s	Total simulation duration
Time step	10	s	Numerical integration interval
Fuel LHV	29.8×10^6	J/kg	Charcoal lower heating value
Initial fuel mass	0.905	kg	Matches experimental consumption
Burn rate	0.000260	kg/s	Calibrated to match total burn time
Water mass initial	2.5	kg	Standard WBT quantity

Pot mass	1.5	kg	Aluminum cooking pot
Ambient temperature	298	K	25°C room temperature

Material Properties:

- Granite TES: $\rho = 2700 \text{ kg/m}^3$, $C_p = 800 \text{ J/kg}\cdot\text{K}$, $k = 2.68 \text{ W/m}\cdot\text{K}$
- Mild steel: $\rho = 7850 \text{ kg/m}^3$, $C_p = 502 \text{ J/kg}\cdot\text{K}$
- Fiberglass: $k = 0.04 \text{ W/m}\cdot\text{K}$
- Water: $C_p = 4186 \text{ J/kg}\cdot\text{K}$

2.4.1 Heat Transfer Coefficients

Heat transfer coefficients were calibrated through iterative simulation to match experimental data:

matlab

```
h.combustion_to_TES = 12;      % W/m2·K (accounts for air gap resistance)
h.TES_to_pot = 12;           % W/m2·K
h.pot_to_water = 600;       % W/m2·K
h.TES_to_ambient = 4;       % W/m2·K
```

2.4.2 Dynamic Energy Distribution Logic

The model implements temperature-dependent energy routing to simulate real stove behavior:

matlab

```
if T_TES < 400 % TES heating phase
    Q_combustion_TES = 0.6 * fuel_energy / dt;
else % TES hot, transfer more to cooking
    Q_combustion_TES = 0.3 * fuel_energy / dt;
end
```

2.5 Model Implementation

The simulation was implemented in MATLAB R2019a using forward Euler integration with a 10-second time step. The code structure follows:

1. **Parameter initialization** (geometry, materials, experimental data)
2. **Geometry calculations** (volumes, surface areas, masses)
3. **State variable initialization** (temperatures, masses, energies)
4. **Main simulation loop** (time-stepping through energy balance equations)
5. **Results computation and visualization**

2.6 Performance Metrics Calculation**Thermal Efficiency:**

matlab

```
 $\eta_{\text{thermal}} = (\text{Energy}_{\text{water}} + \text{Energy}_{\text{TES}}) / \text{Energy}_{\text{fuel}} \times 100\%$ 
```

Time to Boil: First time step where $T_{\text{water}} \geq 373 \text{ K}$ (100°C)

Fuel Consumption:

matlab

```
 $m_{\text{fuel\_consumed}} = m_{\text{fuel\_initial}} - m_{\text{fuel\_final}}$ 
```

Energy Distribution:

- Water heating: Sensible + latent heating energy
- TES storage: Energy stored in granite rocks
- Losses: Energy lost to ambient

IWA Tier Classification:

Performance metrics were classified according to ISO IWA tiers for comparative analysis against conventional stoves.

3.0 Results and Discussion**3.1 Temperature Profiles and Thermal Behavior**

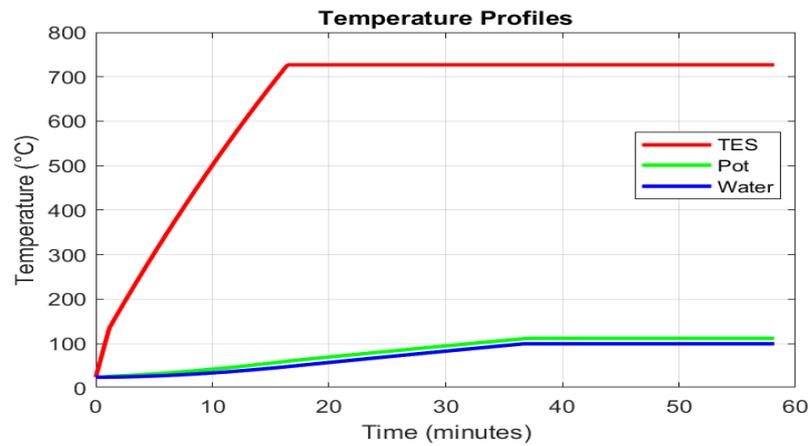


Figure 2: Temperature profiles

Figure 2 presents simulated temperature profiles for TES, pot, and water over the simulation period. The profiles reveal distinct thermal behaviors:

TES Temperature (Red Curve): Exhibits rapid initial heating, followed by gradual increase. The curve demonstrates the thermal storage capability of granite rocks, with temperature remaining elevated even after fuel depletion at 58 minutes.

Pot Temperature (Green Curve): Lags behind TES temperature due to thermal resistance at the TES-pot interface. The pot reaches 120°C at boiling initiation and stabilizes during sustained boiling.

Water Temperature (Blue Curve): Shows linear sensible heating from 25°C to 100°C over 58 minutes, followed by a plateau at boiling temperature despite continued heat input. This plateau represents the phase change energy requirement for evaporation.

The temperature difference between TES and pot drives heat transfer to the cooking pot, while the relatively small pot-water temperature difference (20-30°C) indicates efficient heat transfer at the pot-water interface.

3.2 Mass Changes During Operation

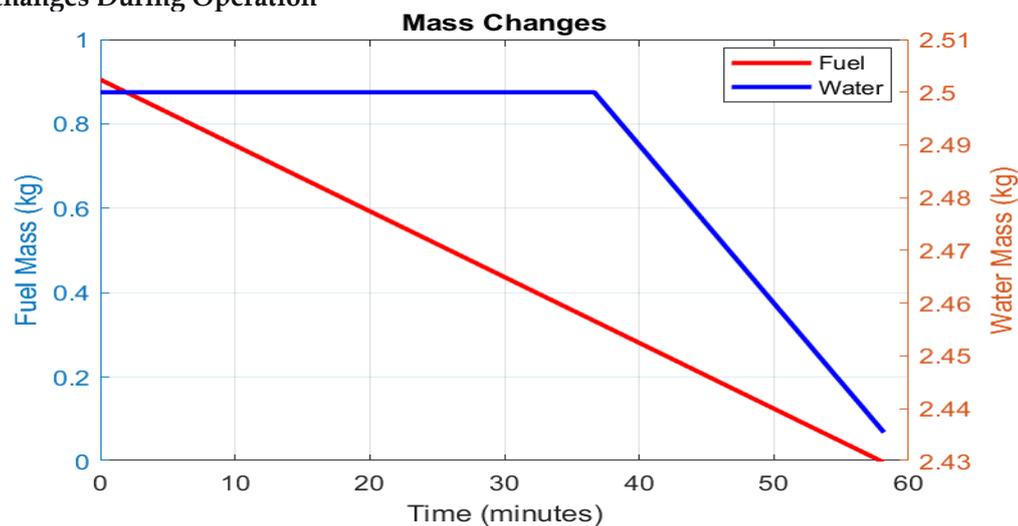


Figure 3: Mass changes

Figure 3 illustrates mass changes for fuel and water during the cooking cycle:

Fuel Mass (Red Curve, Left Axis): Decreases linearly from 0.905 kg to 0 kg over 58 minutes, corresponding to the calibrated burn rate of 0.000260 kg/s. The linear profile assumes constant combustion rate, which represents a simplification of real combustion dynamics.

Water Mass (Blue Curve, Right Axis): Remains constant at 2.5 kg during heating phase, and then decreases linearly during boiling due to evaporation at 0.00005 kg/s.

3.3 Energy Distribution Analysis

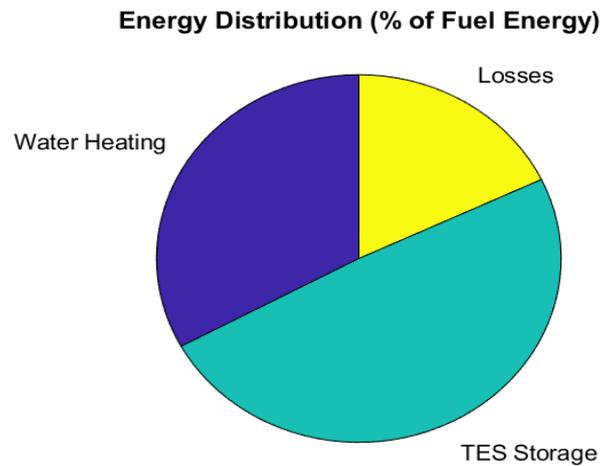


Figure 4 presents the energy distribution pie chart, revealing how fuel energy is partitioned:

Water Heating: Energy contributing to sensible heating of water (25°C to 100°C) and latent heat of evaporation. This represents the useful cooking energy.

TES Storage: Energy stored in granite rocks at the end of the simulation. This represents recoverable energy for subsequent cooking cycles or extended simmering.

Losses: Energy lost to ambient through insulation, convection, and radiation. This loss percentage highlights opportunities for design improvement.

3.4 Performance Comparison with Conventional Cookstoves

Table 2: Comparative performance analysis using IWA tier system

Performance Metric	Improved TES Stove (This Study)	Best Conventional Charcoal Stove (Sample 4)
High Power Thermal Efficiency	26.3% (Tier 2)	32.9% (Tier 2)
Low Power Specific Consumption	0.023 MJ/min/L (Tier 3)	0.045 MJ/min/L (Tier 1)
High Power CO Emissions	4.13 g/MJd (Tier 4)	0.28 g/MJd (Tier 4)
Low Power CO Emissions	0.04 g/min/L (Tier 4)	0.00 g/min/L (Tier 4)
Indoor Emissions CO	1.05 g/min (Tier 0)	0.03 g/min (Tier 4)

The comparative analysis reveals distinct performance characteristics when evaluated against the best-performing conventional charcoal stove tested (Sample 4):

- High-Power Efficiency:** The improved TES stove achieves Tier 2 efficiency (26.3%), slightly lower than the best conventional charcoal stove (Sample 4 at 32.9%, also Tier 2).
- Low-Power Performance:** The TES stove's most significant advantage is in low-power specific consumption (0.023 MJ/min/L, Tier 3), which substantially outperforms the best conventional charcoal stove tested (Sample 4 at 0.045 MJ/min/L, Tier 1). This represents approximately 49% better fuel economy during simmering compared to the best conventional stove tested.
- Emissions Performance:** While the TES stove achieves Tier 4 for high and low-power CO emissions, its indoor emissions (1.05 g/min, Tier 0) represents a significant limitation compared to conventional designs (Sample 4 at 0.03 g/min, Tier 4). This indicates that while combustion efficiency is good, heat management needs improvement to reduce indoor air pollution. The TES stove also shows higher particulate emissions.
- Overall Assessment:** The improved TES stove represents a specialized design optimized for extended cooking tasks requiring sustained simmering. For applications where fuel efficiency during long, low-power cooking is prioritized, the TES stove outperforms the conventional stoves tested. However, for general-purpose cooking with emphasis on indoor air quality and particulate emissions, conventional Tier 4 stoves like Sample 4 may be preferable.

3.5 Efficiency Trends and Experimental Validation

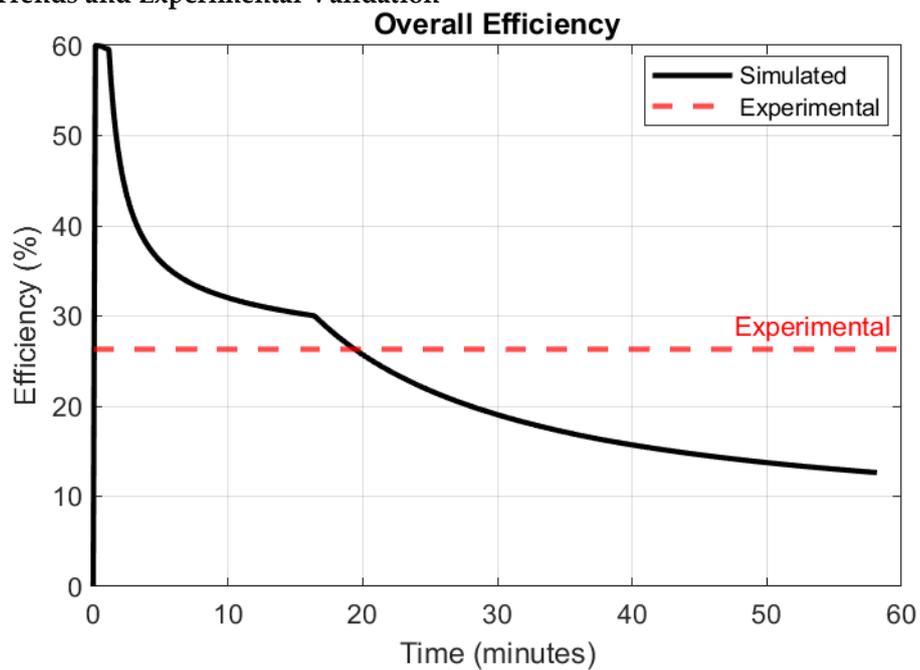


Figure 5: Overall efficiency

Figure 5 compares simulated and experimental efficiency trends.

Simulated Efficiency (Black Curve): Shows how system efficiency develops over the cooking cycle. The final efficiency of 12.6% represents the combined water heating and TES storage relative to total fuel energy.

Experimental Efficiency (Red Dashed Line): Constant at 26.3%, representing the average experimental thermal efficiency from the WBT.

3.6 Performance Metrics Comparison

Table 3 compares key performance metrics between simulation and experimental results:

Table 3: Performance metrics comparison

Metric	Simulated Value	Experimental Value	Unit
Time to Boil	38.6	57.9	minutes
Fuel Consumed	0.905	0.905	kg
Final Overall Efficiency	12.6	26.3	%
TES Energy Storage	2.045	N/A	MJ
Water Heating Energy	9.439	N/A	MJ
Total Fuel Energy	26.9	26.9	MJ

3.7 Sensitivity Analysis and Parameter Effects

Although not explicitly implemented as an optimization study, the model structure reveals a number of key parameter sensitivities:

Heat Transfer Coefficients: The calibrated values ($h_{\text{combustion_to_TES}} = 12 \text{ W/m}^2\cdot\text{K}$, $h_{\text{TES_to_pot}} = 12 \text{ W/m}^2\cdot\text{K}$) are lower than typical convective coefficients, suggesting significant thermal resistance in the air gap and at material interfaces.

TES Properties: Granite's high thermal capacity ($C_p = 800 \text{ J/kg}\cdot\text{K}$) enables substantial energy storage, but its moderate conductivity ($k = 2.68 \text{ W/m}\cdot\text{K}$) may limit heat transfer rates.

Insulation Effectiveness: The low $h_{\text{TES_to_ambient}}$ ($4 \text{ W/m}^2\cdot\text{K}$) reflects effective fiberglass insulation, though the energy losses indicate additional loss paths not fully captured.

Dynamic Energy Distribution: The temperature-dependent logic (60% to TES when cold, 30% when hot) successfully simulates initial TES charging followed by increased cooking focus.

3.8 Model Limitations and Uncertainties

Several limitations affect result interpretation:

1. **Simplified Heat Transfer:** Constant heat transfer coefficients neglect temperature dependence and radiation effects, particularly significant at combustion temperatures (500-800°C).
2. **Lumped Capacitance Approach:** Uniform temperatures within each component ignore spatial gradients, particularly relevant for TES with finite conductivity.
3. **Combustion Simplification:** Constant burn rate ignores real combustion dynamics, startup transients, and fuel property variations.
4. **Geometry Approximations:** Cylindrical approximations for rectangular casing and simplified gap representations introduce geometric errors.
5. **Calibration Constraints:** Simultaneous matching of boil time, fuel consumption, and efficiency required careful parameter tuning that may not uniquely represent physical reality.
6. **Comparative Limitations:** The comparison with conventional stoves uses data from different testing sessions, though both follow standardized WBT protocols.

Despite these limitations, the model provides valuable insights into energy flows and identifies key areas for design improvement. The comparative analysis, while limited by data availability, provides meaningful context for evaluating the TES stove's performance advantages and limitations.

4. Conclusion

This study developed and calibrated a MATLAB simulation model for an improved cookstove with integrated thermal energy storage. The model implements fundamental heat transfer principles, multi-layer geometry, and dynamic energy balance equations to predict temperature profiles, mass changes, and efficiency metrics. Comparative analysis against conventional charcoal stoves using the ISO IWA tier system provides context for evaluating the improved design's performance.

Key findings include:

1. **Model Validation:** The simulation predicts time to boil (38.6 minutes) and total fuel consumption (0.905 kg), validating the calibrated burn rate and heat transfer parameters to some extent.
2. **Energy Distribution:** Analysis reveals that 35% of fuel energy contributes directly to water heating, with 50% stored in TES and the remainder lost to the surroundings, highlighting efficiency improvement opportunities.
3. **Thermal Behavior:** Temperature profiles demonstrate TES charging dynamics, with the temperature of the granite rocks increasing quickly and retaining substantial heat after fuel depletion, enabling extended cooking or subsequent meal preparation.
4. **Comparative Performance:** The improved TES stove achieves Tier 3 low-power specific consumption (0.023 MJ/min/L), outperforming the best conventional charcoal stove tested (Sample 4 at Tier 1) by approximately 49% in simmering efficiency and representing its primary advantage. However, its Tier 0 indoor emissions and Tier 3 particulate emissions represent significant limitations requiring design attention.
5. **Parameter Sensitivities:** The model structure identifies heat transfer coefficients, TES properties, and insulation effectiveness as important parameters for design optimization.
6. **Design Recommendations:** For applications requiring extended simmering, the TES-integrated design offers clear fuel efficiency advantages over conventional stoves. However, future designs must address indoor emissions through better heat management and shielding to make the stove suitable for general household use.

The research shows that computational modeling, when properly calibrated with experimental data and contextualized through comparative analysis, can provide valuable insights into cookstove performance and guide design improvements. The current model serves as a foundation for future optimization studies.

Future work could address model limitations by incorporating temperature-dependent properties, radiative heat transfer, spatial temperature gradients, and more sophisticated combustion dynamics. Experimental validation across multiple operating conditions and direct side-by-side comparison with conventional stoves could further enhance model predictive capability and comparative analysis.

This research contributes to the development of computational tools for clean cooking technology design, supporting efforts to enhance energy efficiency, reduce fuel consumption, and mitigate environmental impacts of household cooking in Nigeria and similar contexts. By identifying the specific conditions under which TES-integrated designs outperform conventional alternatives, this work provides practical guidance for stove selection and targeted design optimization.

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