Effect of Forced Ventilation on the Energy Performance and Emissions of a Domestic Cooking Gasifier

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ABSTRACT

This article evaluates the impact of forced ventilation on the energy performance and pollutant emissions of a domestic biomass micro-gasifier, in comparison with a natural-draft configuration and the traditional three-stone fire, in accordance with the ISO 19867-1 testing protocol. Cooking tests were conducted at high, medium, and low power levels using physico-chemically characterized biomass pellets, with rigorous measurements of thermal efficiency, cooking power, and CO and $PM_{2.5}$ emissions using the Laboratory Emissions Monitoring System (LEMS). The results show that forced ventilation significantly improves combustion performance, increasing the average thermal efficiency to 48.3% (Tier 4), representing an improvement of approximately 24% compared with natural ventilation, while substantially reducing $PM_{2.5}$ and CO emission factors. These improvements are attributed to better control of primary and secondary airflows, which promotes more complete oxidation of combustible gases and reduces incomplete combustion, particularly at low power operation. The study therefore demonstrates that forced-draft micro-gasifiers represent a high-performance and credible solution for clean domestic cooking, especially in Sahelian and West African contexts, by simultaneously enhancing energy efficiency, reducing indoor air pollution, and contributing to the achievement of Sustainable Development Goals related to health and clean energy.

Keywords: Micro-gasifier, natural ventilation, forced ventilation, biomass burning

1. INTRODUCTION

In developing countries, the traditional use of solid biomass fuels (firewood, agricultural residues, charcoal) through inefficient cooking systems such as the “three-stone” stove remains the dominant practice for meal preparation [1-2]. These systems are characterized by low energy efficiency and incomplete combustion, leading to high emissions of air pollutants such as carbon monoxide (CO) and fine particulate matter ($PM_{2.5}$), which are responsible for significant degradation of indoor air quality.

According to the World Health Organization, prolonged exposure to smoke from domestic biomass combustion is one of the leading environmental health risk factors, contributing to several million premature deaths each year, primarily among women and young children [3]. $PM_{2.5}$ and CO concentrations measured in kitchens using traditional stoves are on the order of 500 to 1,000 $\mu g/m^3$ [4], which far exceed the guideline values recommended for indoor air quality [3].

To address this issue, numerous programs have promoted the dissemination of improved cookstoves aimed at reducing fuel consumption and enhancing thermal efficiency. However, several studies have shown that these technologies particularly those relying on natural draft do not always achieve emission levels compatible with international health based recommendations [5]. In response to these limitations, the scientific community and stakeholders in the household energy sector have developed performance frameworks, notably through the ISO 19867 standards, which classify cookstoves based on their thermal efficiency, CO and $PM_{2.5}$ emissions, safety, and durability [6].

In this context, biomass micro-gasifier stoves emerge as a promising technological alternative. Their operating principle, based on controlled gasification followed by combustion of the produced gases, allows for a significant improvement in combustion quality and a reduction in pollutant emissions [7]. The addition of forced ventilation enhances control over primary and secondary airflows, thereby improving the oxidation of unburned compounds and the overall thermal performance of the system. Several studies have shown that ventilated micro-gasifier stoves rank among the most efficient household cooking technologies in terms of emission reduction and compliance with higher ISO performance tiers [8-9-10].

This study aims to evaluate the influence of forced ventilation on the combustion characteristics of biomass fuels, highlighting its effects on improving energy performance and reducing pollutant emissions generated during cooking.

2. Materials and Methods

2.1 Fuel used

The experiments were conducted using biomass pellets with a diameter of 6.5 mm and a length not exceeding 4 cm. The fuel properties were determined through standard laboratory analyses. The moisture content was 6.03% (wet basis), measured using a drying oven (BINDER). Ash content (1.89%) and volatile matter (82.04%) were determined using a Nabertherm muffle furnace, while the fixed carbon content was calculated as 16.07%. The higher heating value (HHV) of the pellets was measured as 19.53 MJ/kg using a Parr 6775 bomb calorimeter. For comparison, the HHV of charcoal was 25.63 MJ/kg.

2.2 Cooking Vessel

A flat-bottom stainless steel pot with a diameter of 24 cm and a height of 20 cm was used during the tests. The pot was filled with 3 L of water, consistent with local cooking practices. No pot skirt was employed.

2.3 Testing Procedure

The cookstove was evaluated following the ISO 19867-1:2018 standard. Tests were conducted at three power levels (high, medium, and low), covering the complete combustion cycle, including startup, steady-state, and shutdown phases (figure 1). A cold start was performed at high power, while medium and low power tests were conducted under hot-start conditions [6].

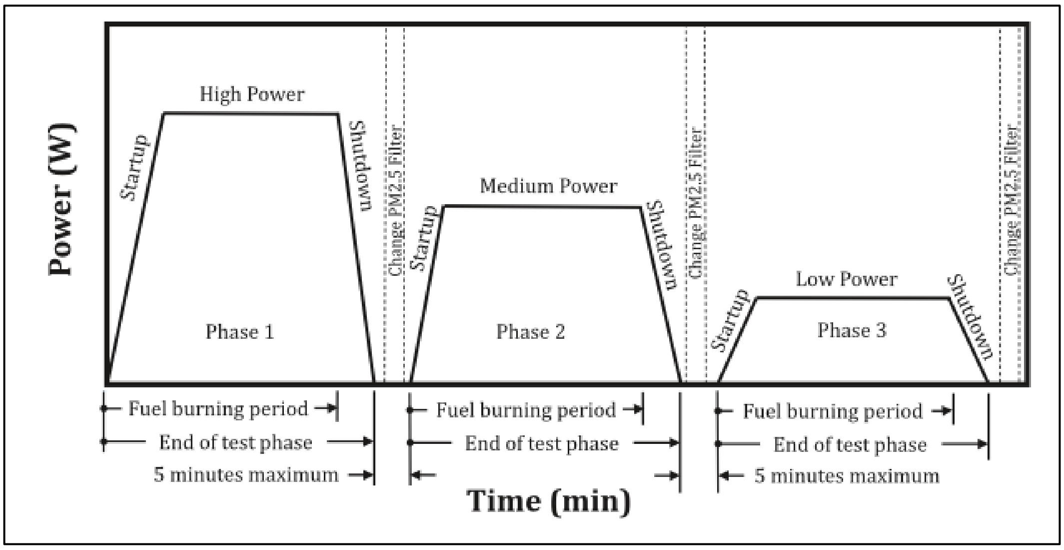

Figure 1: Diagram of the testing phase for a stove tested at only one power level [6].

2.4 Fuel Use and Thermal Performance

Fuel consumption and thermal efficiency were determined based on measurements of fuel mass, water temperature variation, evaporated water mass, and test duration. Fuel mass was measured using a balance with 1g resolution, while water temperature was recorded using a silicone-shielded thermocouple. The fuel moisture content and heating values were used to calculate energy input and thermal efficiency. Thermal efficiency was determined by accounting for the energy contribution of the char residues produced during biomass combustion [6].

$$\Psi_c = \frac{Q_1}{BQ_{net.af} - CQ_{net.char}} \times 100\% \qquad (1)$$

Ψ_c	is the cooking thermal efficiency with energy credit for the remaining char residues (%);
Q_1	is the useful energy delivered, (kJ);
B	is the mass of the input fuel (kg);
$Q_{net.af}$	is the lower heating value of the fuel, as burned, (kJ/kg);
C	is the mass of remaining char residue (kg);
$Q_{net.char}$	is the lower calorific value of the remaining char residues, as burned (kJ/kg).

2.5 Emissions Measurements

Pollutant emissions (CO, CO_2, and $PM_{2.5}$) were measured using the Laboratory Emissions Monitoring System (LEMS) (figure 2), a total-capture dilution tunnel system compliant with ISO 19867-1:2018. Carbon monoxide and carbon dioxide concentrations were monitored using calibrated electrochemical and infrared sensors, respectively. Fine particulate matter ($PM_{2.5}$) was collected on 47 mm glass fiber filters and gravimetrically analyzed using a 0.01 mg resolution balance. Emission factors were calculated based on measured concentrations, dilution tunnel flow rates, and useful energy delivered.

The emission factor is calculated using the Formula (2).

$$\boldsymbol{EF = \frac{M_i}{Q_1}} \qquad \textbf{(2)}$$

EF	is the pollutant emission factor (mg/kJ);
M_i	is the total mass of pollutant emissions during the test (mg);
Q_1	is the useful energy delivered (kJ).

Figure 2: LEMS hood, ducts and gravimetric assembly

3. Results et discussions

In accordance with ISO 19867, the results presented in Tables 1 and 2 correspond to the mean of five repetitions conducted at each of the three power levels of the cooking performance test (high, medium, and low power). The combined values are calculated as the arithmetic mean of the results obtained at the three power levels and are used to assign the stove performance level. Performance levels, expressed as Tiers, range from Tier 1 to Tier 5 based on the thresholds defined in ISO 19867 for each performance indicator.

3.1 Results obtains with the natural ventilation micro-gasifier

Table 1: Results obtains with the natural ventilation micro-gasifier

Metric		Test Sequence Phase				Tier rating
		High	Medium	Low	Combined	
Thermal efficiency with char (%)	Mean	**30.2**	**35.8**	**44.7**	**36.93**	**3**
	SD	0.1	2.6	0.2	1.0	
Cooking power (kW)	Mean	**1.97**	**1.98**	**0.85**	**1.6**	n.a.
	SD	0.28	0.33	0.33	0.3	
Fuel burning rate (g/min)	Mean	**5.54**	**3.52**	**1.58**	**3.55**	n.a.
	SD	1.46	0.91	0.67	1.01	
$PM_{2,5}$ per useful energy (mg/MJ)	Mean	**259**	**480**	**352**	**364**	**2**
	SD	132	160	232	175	
CO per useful energy (g/MJ)	Mean	**2.56**	**5.10**	**6.25**	**4.63**	**3**
	SD	1.02	1.30	3.14	1.82	

The table 1 shows a clear and internally consistent relationship between operating phases (high, medium, and low power) and the energetic and emissions performance of the cookstove, highlighting the widely acknowledged trade-offs in biomass combustion systems. Thermal efficiency with char increases markedly from high (30.2%) to low power operation (44.7%), leading to a combined mean of 36.93% and a Tier 3 performance, which can be attributed to longer residence time of gases, improved char oxidation, and reduced convective heat losses at lower firing rates, as reported in controlled laboratory studies on gasifier and improved biomass stoves [11-12]. In contrast, cooking power and fuel burning rate decrease substantially from high to low phases (1.97–1.98 kW to 0.85 kW and 5.54 to 1.58 g/min, respectively), reflecting reduced thermal output and fuel input, which is typical of low power simmering conditions and explains the higher efficiency but lower delivered power. Emissions normalized to useful energy show more complex behavior: $PM_{2.5}$ per useful energy is lowest at high power (259 mg/MJ) and increases at medium and low power, yielding a combined value of 364 mg/MJ (Tier 2), suggesting that although absolute emissions may drop at low power, incomplete combustion and smoldering conditions increase particulate formation per unit of useful energy delivered [13-14]. Similarly, CO per useful energy rises sharply from high (2.56 g/MJ) to low power (6.25 g/MJ), with a combined mean of 4.63 g/MJ (Tier 3), indicating poorer oxidation conditions at reduced air-fuel ratios and lower flame temperatures. Overall, the results confirm that low power operation enhances thermal efficiency but penalizes emission intensity per useful energy, underscoring the importance of optimized air supply and combustion control particularly for medium and low phases to achieve simultaneous gains in efficiency and emissions performance, as emphasized in the broader improved cookstove literature [6-11].

3.2 Results obtains with a forced ventilation micro-gasifier

Table 2: Results obtain with a forced ventilation micro-gasifier

Metric		Test Sequence Phase				Tier rating)
		High	Medium	Low	Combined	
Thermal efficiency with char (%)	Mean	**32,9**	**49,0**	**63,0**	**48,3**	**4**
	SD	0,6	0,7	1,2	0,83	
Cooking power (kW)	Mean	**2,2**	**2,0**	**1,4**	**1,87**	na
	SD	0,1	0,1	0,3	0.17	
Fuel burning rate(g/min)	Mean	**5,4**	**3,8**	**0,8**	**3,33**	na
	SD	0,3	0,2	0,0	0,17	
$PM_{2,5}$ per useful energy (mg/MJ)	Mean	**179**	**130**	**108**	**139**	**3**
	SD	44	8	10	0,0	
CO per useful energy (g/MJ)	Mean	**7,1**	**8,2**	**4,5**	**6,6**	
	SD	1,0	0,7	1,1	0,9	**2**

The table 2 indicates a strong dependence of stove performance on the operating phase, with clear improvements in efficiency and emission intensity as power decreases, which is characteristic of well controlled biomass combustion without char recovery. Thermal efficiency with char increases substantially from high (32.9%) to low power (63.0%), yielding a high combined mean of 48.3% (Tier 4), reflecting longer heat transfer times, reduced excess air losses, and more effective utilization of volatile gases during low power operation, as widely reported for improved and gasifier type cookstoves [11-12]. In parallel, cooking power and fuel burning rate decrease from high to low phases (2.2 to 1.4 kW and 5.4 to 0.8 g/min, respectively), illustrating the classic trade-off between delivered power and efficiency, where simmering conditions favor efficiency but limit thermal output. Emissions normalized to useful energy show comparatively good performance, $PM_{2.5}$ per useful energy declines steadily from 179 mg/MJ at high power to 108 mg/MJ at low power, resulting in a combined value of 139 mg/MJ (Tier 3), suggesting that improved combustion stability and reduced fuel throughput lower particulate formation per unit of useful energy, consistent with laboratory findings on advanced biomass stoves [14]. CO per useful energy exhibits a non-monotonic trend, peaking at medium power (8.2 g/MJ) and decreasing at low power (4.5 g/MJ), with a combined mean of 6.6 g/MJ (Tier 2), which may indicate transitional combustion regimes at medium load where air fuel mixing and oxidation are less optimal. Overall, these results demonstrate that low power operation without char recovery maximizes thermal efficiency and minimizes $PM_{2.5}$ intensity, while CO emissions remain more sensitive to combustion control, underscoring the need for optimized air supply and operating practices to simultaneously achieve high efficiency and low emissions, in line with ISO 19867-1 performance assessments [6].

3.3 Difference between Forced ventilation et Naturel ventilation

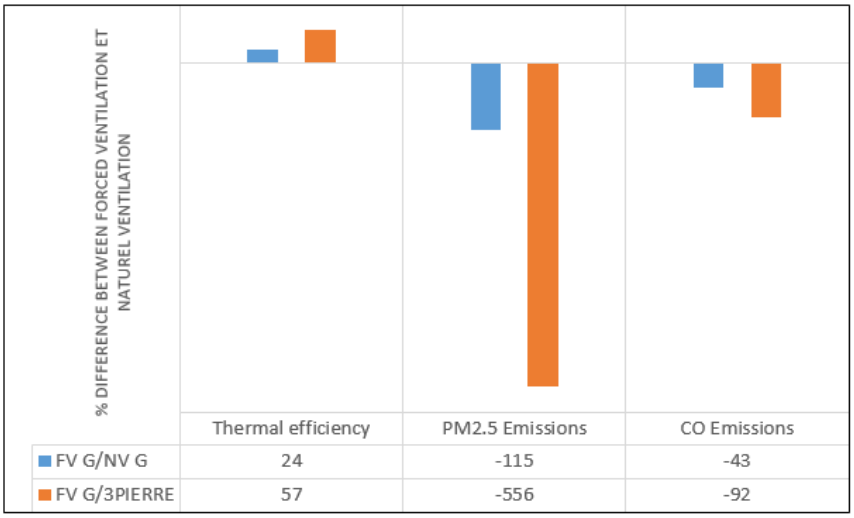

Figure 3: % Difference between Forced ventilation et Naturel ventilation

The graph 3 highlights the clear superiority of the forced-draft micro-gasifier in terms of both energy performance and pollutant emissions compared with the natural-draft micro-gasifier and the traditional three-stone fire. Thermal efficiency increases by about 24% under forced ventilation, and even more markedly relative to the three-stone stove, as the controlled airflow enhances solid fuel gasification, promotes more complete oxidation of combustible gases (CO, H_2, CH_4), and reduces heat losses, leading to higher and more stable flame temperatures and improved heat transfer to the cooking pot; this contrasts with the poorly controlled, draft dependent combustion of three-stone fires, and is consistent with reported efficiencies of 30–45% for forced-draft gasifiers versus 10–15% for traditional stoves [11-15-16]. In parallel, $PM_{2.5}$ emissions are drastically reduced, by up to about 115% relative to the three stone fire and significantly compared with natural draft, reflecting much more complete combustion in the forced draft system, where controlled air supply oxidizes fine particles formed during biomass pyrolysis and limits soot and carbonaceous aerosol formation; by contrast, the three stone fire operates largely under incomplete combustion with cold zones and poor air fuel mixing, conditions known to favor $PM_{2.5}$ generation, while the literature reports 70–90% (or greater) $PM_{2.5}$ reductions for fan assisted gasifier stoves, sometimes approaching WHO indoor air quality guidelines [17-11-2]. Finally, carbon monoxide emissions decrease by roughly 43% with forced ventilation compared with natural draft and even more relative to the three stone fire, confirming enhanced oxidation of carbon to CO_2, since CO is a direct indicator of incomplete combustion; natural draft systems are prone to airflow fluctuations that generate CO rich phases during ignition and refueling, whereas three-stone fires often exceed WHO recommended limits, while experimental studies show that forced-draft micro-gasifiers can reduce CO emissions by 40–80% depending on fuel type and operating conditions [15-18].

Conclusion

The systematic comparison between the two configurations clearly demonstrates that the integration of forced ventilation constitutes a major technological lever for enhancing the overall performance of micro-gasifiers designed for domestic cooking. Precise control of the air supply promotes more complete gasification of the fuel, resulting in a significant increase in energy efficiency and a marked reduction in fine particulate matter ($PM_{2.5}$) emissions, a key indicator of indoor air pollution.

By achieving performance levels consistent with the thresholds recommended by the World Health Organization (WHO) and Clean Cooking initiatives, the forced ventilation micro-gasifier emerges as a credible solution for the transition toward cleaner and more sustainable cooking systems.

These findings are particularly relevant for Sahelian and West African contexts, where reliance on solid biomass remains high, pressure on woody resources is increasing, and household exposure to health risks associated with domestic air pollution is significant. Large scale adoption of this technology could therefore simultaneously contribute to improving living conditions, reducing environmental impacts, and advancing the achievement of the Sustainable Development Goals, particularly those related to health, clean energy, and climate action.

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