Validation and comparatibe assessment of an improved wood-burning cookstove under controlled conditions and in the field[1]

Validación y evaluación comparativa de la eficiencia de una estufa de leña mejorada bajo condiciones controladas y prueba de campo

Received: 03 - 03 - 2014 Accepted: 10-05-2014

Javier Dario Aristizabal Hernández[2]

Abstract

To assess the efficiency and potential saving of fuelwood of a new and improved prototype of wood-burning cookstove, three well-known protocols were used: (1) the water boiling test (WBT), which assesses thermal efficiency, boiling time, burning rate, and specific fuel consumption (SFC); (2) the controlled cooking test (CCT), which was implemented in 30 rural households to establish the cookstove's efficiency in terms of SFC; and (3) the kitchen performance test (KPT), also applied in 30 rural households, to measure impact in real household conditions. The improved cookstove presented 15% thermal efficiency, representing a 33% saving in fuelwood. In contrast, the CCT showed a 13.4% reduction in fuelwood consumption, whereas the KPT showed an 11.6% decrease. These research results confirm the findings of other studies in that the efficiency of improved cookstoves under controlled conditions does not necessarily relate to the fuelwood savings achieved when cookstoves are evaluated in a real kitchen environment.

Key words: Improved cookstove; thermal efficiency; fuelwood consumption.

Introduction

According to Colombia's National Administrative Department of Statistics (DANE, its Spanish acronym), 14% of the country's population, mostly that in rural areas, relies on fuelwood as main source of fuel for cooking food food (DANE, 2008). Fuelwood is used either in three-stone fires or traditional wood-burning cookstoves with less than

[1] Research was carried out between March and December 2013 under the project "Mechanism for the voluntary mitigation of carbon emissions in Colombia (CO-X1008)". This part of the project was executed by the Fundación Natura Colombia and financed by the Global Environment Facility (GEF) and the Inter-American Development Bank (IDB).

[2] Colombian, Forest Engineer, Specialist in Environmental Planning and Integrated Natural Resource Management. E-mail: jaristizabal@ natura.org.co.

10% efficiency, demanding high volumes of fuelwood to meet specific cooking requirements. According to Kissinger et al. (2012), this demand for fuelwood for household cooking and charcoal production has reduced and degraded forest cover, affecting forest and their biodiversity. Such issue is more relevant in Africa than in Asia and Latin America"

In addition, the use of three-stone fires has a negative impact on the environment and people's health. Indoor air pollution *is responsible* for 1.5 million deaths annually worldwide, mainly affecting women and children (WHO, 2006). The frequent exposure to smoke produced by the burning of fuelwood is known to be strongly related to respiratory diseases such as chronic obstructive pulmonary disease (COPD), pneumonia, and asthma, as well as with several types of ophthalmic morbidity (WHO, 2006). Larsen (2004) indicated that, nationwide, indoor air pollution is responsible for 16-25% of child morbo-mortality among the total population affected by acute respiratory infection (ARI) and for 15-35% morbo-mortality in women, caused by COPD.

The inefficient combustion of fuelwood produces highly contaminating substances such as carbon monoxide (CO), particulate matter (PM_{10} and $PM_{2.5}$), and even persistent organic pollutants (POPs) that are released into the atmosphere in concentrations well above permissible limits (WHO, 2006). A study conducted by Colombia's Ministry of Environment, Housing, and Territorial Development (MAVDT, its Spanish acronym) in 2007 indicated that household burning of fuelwood accounted for 9% of the nation's dioxin and furan emissions (MAVDT, 2007). The use of three-stone fires or inefficient wood-burning stoves contributes to the emission of greenhouse gases (GHGs) into the atmosphere. The inefficient combustion of fuelwood is responsible for generating not only carbon dioxide (CO_2) but also other gases with much higher potential global warming effects, such as carbon monoxide CO, methane (CH_4), and different nitrogen oxides (NO_x).

It has recently been established that black carbon, a type of particulate material mainly composed by elemental carbon, also have a strong global warming potential, ranking second after CO_2 as greenhouse effect agent (Bachman, 2009). Soot production is inherent to the incomplete combustion of fuelwood. Because household cooking has direct implications for each of the aforementioned issues, improving fuelwood combustion will not only have a beneficial effect on human health but on the overall environment as well.

Current endeavors are focused on developing and implementing improved cooking technologies that replace the traditional systems used for centuries by many rural communities, especially in developing countries. However, researchers and academics agree that new cooking technologies should meet minimum performance standards in terms of efficiency, emissions, and safety (Global Alliance for Clean Cookstoves, 2013). Energy efficiency has typically been the main indicator to determine the performance of a new cooking system measured by standardized protocols (see Table 1).

Table 1. Protocols used to measure energy efficiency.

Protocol	Acronym	What it measures	Conditions in which it is conducted
Water boiling test	WBT	Cookstove thermal efficiency (in a direct way)	Under controlled conditions; considered as a laboratory test
Controlled cooking test	CCT	Specific fuel consumption (SFC) as proxy variable of efficiency	Under controlled conditions; considered as a laboratory test
Kitchen performance test	KPT	fuelwood savings	Under real operational conditions of the new technology; carried out under a normal kitchen routine

Source. The authors

This study aimed to determine the thermal efficiency of a new and improved wood-burning cookstove model by applying the following three standardized tests: water boiling test (WBT); controlled cooking test (CCT), and kitchen performance test (KPT). It also determined the difference between its efficiency under controlled conditions and when used in a real cooking environment and the actual Under controlled conditions; considered as a laboratory test fuelwood savings.

Materials and Methods

The improved FN Cookstove is a new prototype of wood-burning cookstove designed by the Fundación Natura and spin off on the ICA-1791 cookstove developed in the 80s by the Colombian Agricultural Institute (ICA, its Spanish acronym). Although its external appearance is very similar to that of the ICA-1791 cookstove, it differs in the shape of its combustion chamber, which adopted the "rocket" design being implemented by cookstove models worldwide (Bryden ., 2005; MacCarty *et al*., 2008). Under this design concept, the combustion chamber has an angular shape, with fuel bed ignition located on its horizontal part and the riser on its vertical part. To reduce conduction heat losses, the combustion chamber is built with refractory silico-aluminous brick to generate adequate thermal insulation. The chamber's rectangular cross-section has an area of 280 cm^2. A detailed description of the FN cookstove can be found in Aristizabal (2010).

Study site

Tests were carried out in the department of Santander, located in northeastern Colombia, in two rural communities: La Purnia, located in the municipality of Los Santos (6°52'N and 73°06'W), and San Isidro, located in the municipality of Zapatoca (6°53'N and 73°13'W). Both rural communities have very similar climatic conditions, with average annual temperatures of 25 °C and average annual rainfall of 1,000 mm. La Purnia is located at 1,150 m above sea level and San Isidro at 1,350 m above sea level.

Selection of families and building of cookstoves

To ensure statistically significant results taking into consideration the high variability occurring in the KPT (Bailis *et al*., 2007; Harvey and Thomas, 2011), 30 households were selected from among volunteer households, 15 from each rural community. Selected households had to meet the following criteria: they had to use fuelwood as the predominant fuel in their daily cooking activities and have a clear need to replace their traditional three-stone fires with the new stove (Figure 1). Each of the selected households was evaluated regarding fuelwood consumption, and a FN cookstove was built for the household to use.

Figure 1. (a) Traditional three-stone fire; (b) improved FN stove; and (c) improved FN stove with external chimney.

Materials used

The materials and equipment used in each protocol are presented in Table 2.

Table 2. Materials and equipment used in each protocol

Amount	Material	Protocol		
1	LEXUS digital scale, 6-kg capacity and 0.2-g precision	WBT	CCT	
1	LEXUS digital hanging scale, 50-kg capacity and 0.1- kg precision	KPT		
1	DIGI-SENSE digital thermometer with liquid immersion thermocoupler	WBT		
1	GE-PROTIMETER Timbermaster moisture tester	WBT	CCT	KPT
1	Chronometer	WBT	CCT	
1	Flexometer	WBT		
4	7-L cooking pots	WBT		
4	2.5-L cooking pots	CCT		
4	Wooden support for thermocouple	WBT		

Source. The authors

The following ingredients were used in each CCT: 500 g rice; 500 g cassava (peeled); 1,800 g water; 30 g cooking oil; 70 g green onions; 20 g salt; and 5 kg fuelwood.

Water boiling test (WBT)

One of the 30 households participating in the study was selected at random to determine the thermal efficiency of the FN stove by applying the three phases of the WBT version 4.2.2. These phases are as follows:

• High power -*Cold start*. A pot filled with 5 L water was placed on each burner (Figure 2a) and initial water temperature recorded as determined by placing the thermocouple 5 cm above the pot bottom. The cookstove was lit with pre-weighed fuelwood (approximately 5 kg) and, once the fire was powerful enough to not extinguish, the timer was started. The purpose of this phase is to achieve, as soon as possible, the local boiling point in the pot placed on the main burner (Figure 2b). The time to boiling point of the water in this pot was recorded and then all fuelwood was removed from the cookstove. Sticks still burning were extinguished and then weighed together with the leftover wood not used in the stove (The Water Boiling Test, 2013). Charcoal was removed from the combustion chamber and subsequently weighed on a Lexus digital scale (Figure 2c). Temperatures reached in each of the pots were recorded. The hot water was then discarded to begin the second phase of the test (The Water Boiling Test, 2013).

• *High power - Hot start*. Four 7-L pots were quickly filled with 5 L pre-weighed water at room temperature. Water temperature in each pot was again measured and pots were placed on stove burners. Fire was ignited using 5 kg pre-weighed fuelwood, and the timer was started once the fire was strong enough to not extinguish. As with the cold-start test phase, this second phase aimed to make the water in the pot on the main burner reach local boiling temperature, after which the same procedure described for the cold-start phase was applied, except that the charcoal remaining in the combustion chamber was not weighed (The Water Boiling Test, 2013).

• The last phase of the test consisted in keeping Low power (simmering) hot water of pot on the main burner just below local boiling point but without letting it hot water of pot on the main burner just below local boiling point more than 6 °C below that temperature, which, for purposes of this study, should not be below 89 °C. The local boiling point calculated for the test site was 95 °C. This last phase of the test was performed over a 45-min period, using the minimum amount of fuelwood possible. The cookstove was lit again with weighed wood and the timer was started once the fire was strong enough to not extinguish. The pot that had reached local boiling point in the previous phase (in other words, the pot on the main burner) was again placed on the cookstove with the thermocouple immersed to monitor temperature, which should remain 3 °C below boiling point but without falling more than 6 °C below this temperature or else the test would be invalidated.

At the end of the 45 min, final water temperature was recorded and unburned pieces of fuelwood were removed as well as the charcoal. Finally, both the pot with fuelwood was weighed apart from charcoal water and the fuelwood was weighed apart from charcoal were weighed (The Water Boiling Test, 2013).

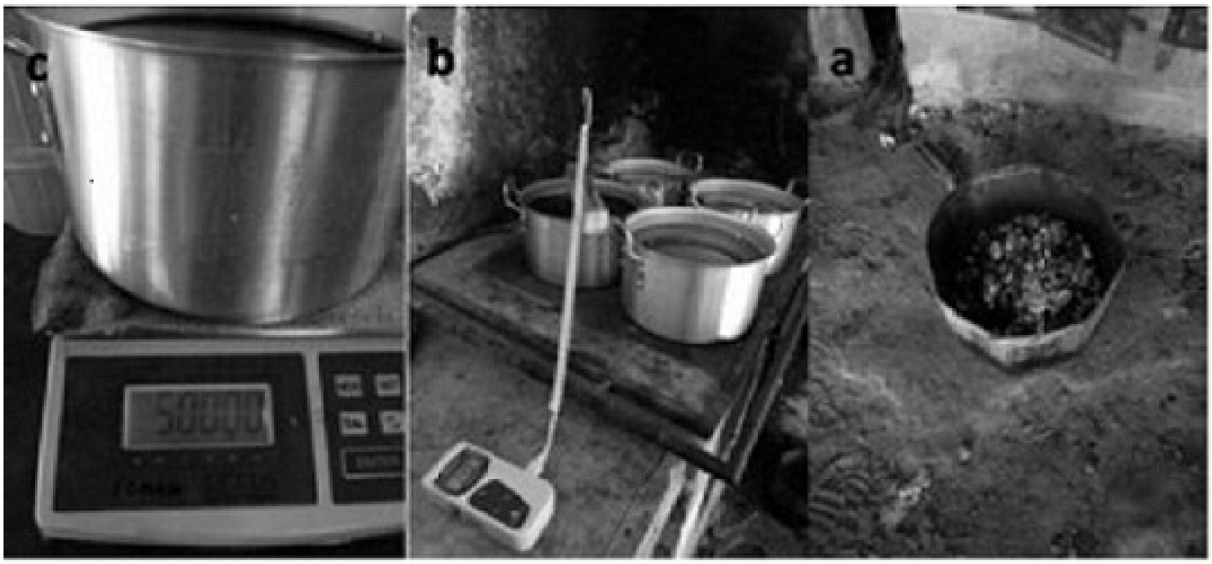

Figure 2. Water boiling test (WBT): (a) charcoal weighed in the cold-start and simmering phases; (b) local boiling point; (c) standard WBT.

Data were recorded in the field data sheet and then systematized in the WBT data worksheet. Each test was replicated five times. Wood tree species *guamo* (*Inga edulis*) was used. The test aimed to determine cookstove performance based on four key measurements: thermal efficiency, boiling time, burning rate, and specific fuel consumption (SFC). For a more detailed description of the methodological approach as well as the application to establish test results, please consult the Water Boiling Test Protocol v. 4.2.2 (2013).

Controlled cooking test (CCT)

The CCT version 2.0 was implemented by the 30 households selected for this test. To assess cookstove performance, a typical rice-and-cassava dish was prepared. Cooking performance of three stone fire and FN cookstove was compared (Bailis, 2004). The test was performed under controlled conditions, and a couple of variations were introduced into the standard CCT:

• Each household participating in the study had its own cooker (housewife) who performed the test using both the traditional three-stone fire and the improved cookstove. To avoid bias in study results, all operators were given the same instructions.

• Each household participating in the study supplied its own fuelwood for each of the tests. In most households, the fuelwood did not come from the same source, which meant that the fuelwood was heterogeneous in terms of composition and moisture content.

Because of the abovementioned modifications, the test was not as strictly controlled as suggested by the protocol, which could ultimately affect the overall outcome of the parameter being measured. However, a semi-controlled version of the CCT was conducted to establish actual cookstove performance in a context that resembles more closely a normal cooking routine as demonstrated by Adkins *et al*. (2010).

The typical rice-and-cassava dish selected for this study is consumed not only in the department of Santander where the study was conducted, but also in other regions of Colombia. Its preparation basically consists in cooking both the rice and the cassava in water until tender enough for consumption. Each food is cooked separately in its own pot.

Rice was cooked in a 2.5-L pot to which 30 g cooking oil, 10 g salt, and 70 g previously chopped green onions had been added. In another 2.5-L pot, 500 g pre-peeled, washed, and weighed cassava were placed with 800 g water and 10 g salt. The cookstove or three-stone fire cooker then lit the stove or fire and, once the fire was strong enough to not extinguish, started the timer to begin the test.

The pots were placed on the cookstove at the same time. In the case of rice, the cooker sautéed the onion and salt in hot cooking oil for approximately 3 minutes before adding 1 L water. Once the water came to a boil, the rice was added and heat was maintained high until the water evaporated completely. Once the rice was "dry", the heat was lowered to a gentle simmer until rice grains expanded and became "fluffy"—their optimal cooking point—due to the joint action of moisture and heat.

The pot containing the cassava, water, and salt was brought to a boil over high heat until the cassava became tender. Optimum cooking point of the cassava was determined by the cooker piercing the cassava with a table fork. However, the procedure used with the improved stove differed from that used with the traditional cookstove. On the improved cookstove, the pot containing the rice was placed on the main burner (where it was directly exposed to the fire), and the pot containing the cassava was placed on one of the two secondary burners. As soon as the water completely evaporated in the pot containing the rice, this pot was moved to a tertiary burner where the low heat allowed the rice to achieve it optimum cooking point, without scorching. The pot containing the cassava was then placed on the main burner to speed up its cooking process.

The test concluded when cassava had properly softened. The cooker then stopped the timer and recorded the time elapsed. Both pots were removed from the cookstove and their contents weighed. In the case of the pot containing the cassava, it was weighed along with the water still remaining in it. All burning fuelwood was smothered and removed from the cookstove, breaking off the charred tips and placing them on a tray. Leftover fuelwood was weighed, including that partially burned. Charcoals were also removed from the combustion chamber and weighed along with the charred tips. The test was replicated three times per household, on both the traditional cookstove/ three stone fire and the improved stove. Bailis (2014) provides a detailed description of the steps involved in the abovementioned test.

Kitchen performance test (KPT)

The real impact of introducing the new cooking system on household consumption of fuelwood was determined under field conditions. Different aspects of the performance of the new technology were evaluated, and the fuelwood consumption of the new system was quantitatively compared with that of the traditional three-stone fire (or other type of traditional cookstove) in a real operational context (Bailis *et al*., 2007). The evaluator did not interfere with the normal cooking routine to avoid unreal situations. Because there was no previous data that could be used to define a statistically significant sample size, the minimum number recommended for further testing by Harvey and Thomas (2011), 30 households, was selected as sample size.

Participating households were not selected at random, but were households that had expressed their interest in participating in the exercise. Participants were informed of KPT requirements and potential complications that could arise during the 6-day testing period (3 days evaluating fuelwood consumption using the traditional three-stone fire and 3 days evaluating fuelwood consumption using the improved cookstove). A paired-sample approach was used, which means that the same 30 households were evaluated before the introduction of the improved FN cookstove and then again after its introduction.

The procedure used to assess household fuelwood consumption was as follows:

- The monitoring team defined the time and day on which participating households would be visited. To avoid disturbing the daily household routine and ensure that family members would be available, visits were made from 5 to 7 p.m.

- Each participating household was visited the day before each test to prepare the fuelwood that would be used the following day. Based on previous monitoring experiences, 20 kg was determined to be the appropriate amount of fuelwood to conduct the KPT and ensure that sufficient fuelwood would be left over for weighing at the end of the day. Fuelwood was weighed using a LEXUS digital hanging scale, 50-kg capacity (reference: Xenit) (Figure 3a).

• Four sticks of fuelwood were randomly selected from the bundle and their moisture contents were measured at three different sampling points using a GE-PROTIMETER Timbermaster moisture tester. Results were averaged and recorded in the field template (Figure 3b).

• Each household adapted a special space for storing the fuelwood that would be used in the KPT so it would not be mixed with fuelwood that had not been considered for testing. Households were encouraged to only use weighed fuelwood for cooking the following day.

Next day, the household, the household was visited at the scheduled time and the fuelwood left over after cooking the last meal of the day was weighed (Figure 3c) and recorded in the field template cookerwere asked to indicate the number of people fed at each meal by gender and age (see Table 3).

• This classification helped determine the adult equivalent fraction per household, a key factor when calculating fuelwood consumption per person.

• The aforementioned procedure was repeated during the 3 days of testing in both first (traditional cookstove) and second phases (improved cookstove). The test was conducted on weekdays to avoid the strong fluctuations in fuelwood consumption that could occur on weekends because of possible non-typical cooking labour on these days (Bailis *et al*., 2009; Harvey and Thomas, 2011).

The timeframe of the first and second phase of monitoring covered approximately 45 days. During this time an improved FN cookstove was built in each one of the households participating in the study. Sufficient time was allowed for the cookstove to dry up and for cookers (housewives) to become familiar with how the cookstove worked before conducting the test.

Figure 3. Kitchen performance test (KPT): (a) initial weighing; (b) recording of moisture content; (c) weighing of leftover fuelwood.

Table 3. Adult equivalence factors defined in terms of gender and age

Gender	Age
Male	Between 15 and 59 years old
Female	Older than 14 years old
Male	Older than 59 years old
Children	Younger than 14 years old

Source. The authors

Results and Discussion

Thermal efficiency

Thermal efficiency is the most important parameter of the WBT and is defined as the fraction of heat produced by the fuel that is transferred to the receptor object (pot). Because it is a dimensionless measurement, it is usually expressed in percentage values. In the case of massive multi-pot cookstoves, thermal , thermal efficiency is calculated based on the following equation:

$$hc = \frac{\left[4{,}186 * \left(\sum_{j=1}^{4}(Pjci - Pj) * (Tjcf - Tjci)\right] + 2260 * Wcv\right.}{fcd * LHV}$$

where hc = thermal efficiency, Pjci = initial weight of water-filled pot "j", Pj = weight of pot "j", Tjcf = final temperature of water-filled pot "j", Tjci = initial temperature of water-filled pot "j", Wcv = amount of evaporated water, fcd = amount of dry wood consumed, and LHV = lower heating value.

Table 4 shows the individual results of each of the five WBTs performed on the FN stove. These results were used as basis for the general discussion of test results.

The thermal efficiency of the FN cookstove during the cold-start phase was 14.2 ± 1.3%, increasing to 16.6 ± 1.1% in the hot-start phase (Figure 4). These findings are consistent with those reported for large cookstoves, whose performance is low when cold-started because the larger cookstove size retains more thermal energy, thus reducing the amount of heat transferred to the receptor (pot). Once the cookstove is hot, heat transfer increases and thermal efficiency improves (Bailis et al., 2007).

The performance of the cookstove during the simmering phase was, however, poor because thermal efficiency was only 7 ± 0.4%. This means that the FN cookstove requires more fuelwood to cook at low power. Overall thermal efficiency of the FN

Table 4. Water boiling test (WBT) results by phase.

Phase	Metrics	Unit	T1	T2	T3	T4	T5		
Cold start	Time to boiling point of pot 1	min	42	49	57	63	51	52.4	7.98
	Burning rate	g/min	49	52	42	48	50	48.2	3.26
	Thermal efficiency	%	16	13	15	13	14	14.2	1.30
	Specific fuel consumption	g/L	168	201	195	236	195	199	24.32
Hot start	Time to boiling point of pot 1	Min	32	26	34	39	32	32.6	4.67
	Burning rate	g/min	63	69	55	50	56	58.6	7.44
	Thermal efficiency	%	15	17	18	16	17	16.6	1.14
	Specific fuel consumption	g/L	164	142	145	154	143	149.6	9.34
Simmering	Burning rate	g/min	37	37	37	31	40	36.4	3.29
	Thermal efficiency	%	8	7	7	7	7	7.2	0.45
	Specific fuel consumption	g/L	384	373	325	313	405	360	39.38

Source. The authors

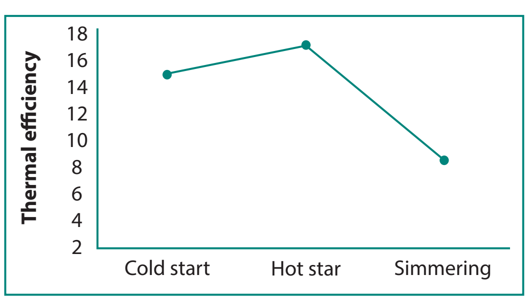

Figura 4. Thermal efficiency during the three phases of the water boiling test (WBT)

cookstove is 15% (the mean value between cold-start and hot-start phases) (DeFoort et al., 2014).

Time to boiling

The time to boiling is defined as the time needed for the cookstove to heat the water in the main pot to local boiling point. It took the FN cookstove an average of 52.4 ± 8 minutes to reaching local boiling point in the cold-start phase as compared with 32.6 ± 4.6 minutes during the hot-start phase (Figure 5). The comparison of means using the Student's *t*-test indicated statistically significant differences at the 95% confidence level between the two phases regarding the time it takes to reach boiling point. Cooking time is reduced by 37% if the stove is used hot.

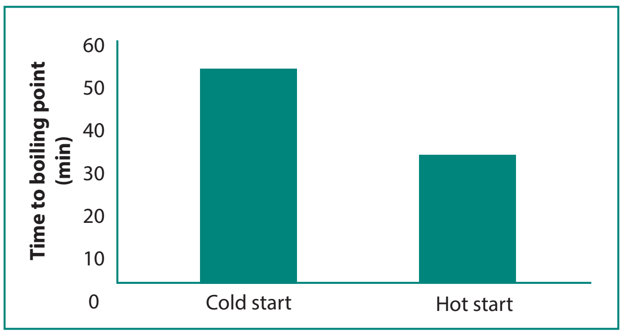

Figure 5. Comparison of time to boiling point between cold-and hot-start phases

Burning rate

This measurement is defined as the amount of fuel (fuelwood) burned per unit time. Average burning rate was 48.2 ± 3.7 g/min in the cold-start phase, increasing to 58.6 ± 7.4 g/min in the hot-start phase (Figure 6). An already hot cookstove tends to foster flame turbulence, increasing the rate of diffusion to the rest of the fuelwood. The burning rate decreased to 36.4 g/min in the simmering phase, a logical outcome because low firepower tends to present a laminar behavior and heat diffusion rate is accordingly lower.

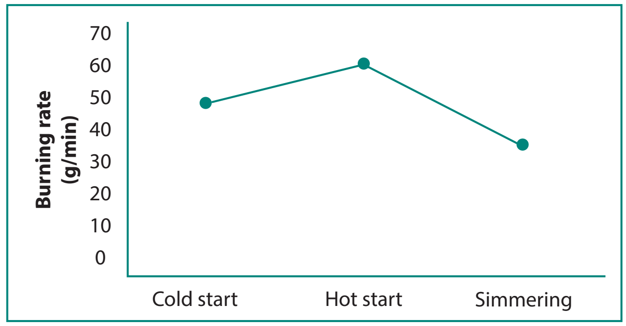

Figura 6. Burning rate fuelwood during the three phases of the water boiling test (WBT).

Specific fuel consumption (SFC)

The SFC in the WBT was 199 ± 24.3 g/L (equivalent to 199 g/kg) in the cold-start phase, 149 ± 9.3 g/L (equivalent to 149 g/kg) in hot-start phase, and 360 ± 39.3 g/L (equivalent to 360±39.3 g/kg) in the simmering phase (Figure 7). The comparison of means using the Student's *t*-test also indicated significant differences between results. Again, performance improves 25% when cooking is done on an already hot cookstove as compared with starting cooking on a completely cold cookstove. Similar to thermal efficiency, overall SFC is defined as the average of results of the cold- and hot-start phases (174 g/L). Performance decreases by more than 50% when the cookstove works at low power (simmering) because SFC doubles as compared with phases of high thermal intensity, evidencing that a correlation exists between thermal efficiency and SFC that tends to be inversely proportional.

- In the second protocol (CCT), SFC was 721.19 ± 288 g/kg for the FN stove, indicating a difference of more than 360% between the two tests attributable to the conditions under which each was performed. In the WBT, the cookstove was assessed at 100% capacity, in other words, pots were placed on all four burners, whereas in the CCT only two burners were used because the test only required the use of two pots. When the WBT was adjusted to consider the use of only two burners, SFC was found to increase to 309.5 g/kg, reducing the difference between both tests to 233% (Figure 7).

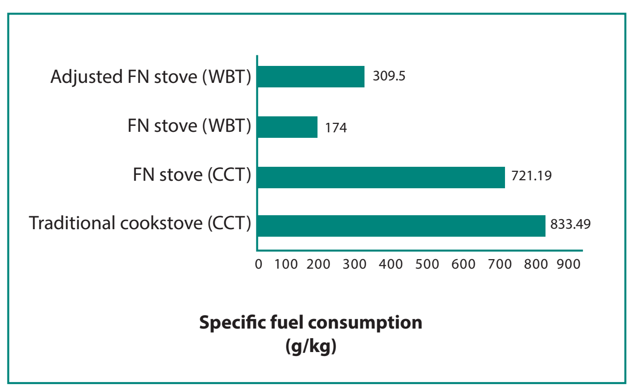

Figura 7. Comparison of specific fuel consumption (SFC) achieved by WBT and CCT for the FN cookstove and the traditional cookstove

- For comparing, specific fuel consumption of three stone fires was also measured. Mean SFC was 833.49 ± 287 g/kg (Table 5). The comparison of means using the Student's *t*-test indicated significant differences at the 95% confidence level. The FN stove consumes 13.4% less fuelwood as compared with the traditional wood-burning stove when similar cooking tasks are performed.

This figure is comparable to that found by Aristizabal (2010) in a previous study that measured the SFC of three prototypes of the FN stove as compared with that of a traditional three-stone fire, giving a difference of 14.66%.

Table 5. Results of the controlled cooking test (CCT) and amount of fuelwood consumed per household (KPT) before and after using the FN cookstove.

	CCT		Fuelwood consumption	
Household	SFC of three-stone fire (g/kg)	SFC of FN cookstove (g(kg)	Traditional three-stone fire (kg/person per day)	FN cookstove (kg/person per day)
Average	833.49	721.19	4.64	3.92

Source. The authors

However, breaking down the assessment per household indicated that in 23% of the involved households the traditional three-stone fire outperformed the FN stove, with SFC values ranging from 3% to 29%. In contrast, in the remaining 77% of the households the FN stove performed better, presenting SFC values between 3–78%, evidencing the heterogeneity of the design of traditional three-stone fires in **i**nvolved households. Some three-stone fires were involved designs with partially enclosed fire, while in others the fire was completely exposed to air, directly impacting heat transfer within the system and, as a result, thermal efficiency.

Fuelwood consumption

The real impact of a new cooking device on household fuelwood consumption can only be assessed on basis of changes in fuelwood consumption patterns. The KPT conducted in the 30 involved households both before and after the introduction of the new stove brought about no conclusive results regarding potential fuelwood savings. Results varied broadly between households because of the highly dispersed data (see Table 5), ranging from negative values in households where fuelwood consumption increased with the introduction of the cookstove to positive values in households where the FN cookstove showed lower fuelwood consumption per person as compared with the traditionally used three-stone fire. Average domestic fuelwood consumption in the reference scenario (traditional three-stone fire) was 4.64 ± 2.5 kg/person per day, decreasing to 3.92 ± 2 kg/person per day when the FN stove was used. The respective coefficients of variation for each scenario (fuelwood consumption before and after the introduction of improved cookstove) were 55% and 51%, agreeing with those reported regarding data variability (Bailis *et al*, 2009).

The Shapiro- wilk test was used to assess the normality of study observations, indicating that results did not respond to a normal distribution. The Wilcoxon signed-rank test was accordingly used to determine the differences between the medians calculated for both tests. Statistically significant differences were found between both parameters at the 95% confidence level. In the study population, a decrease in domestic fuelwood consumption of 0.54 kg/person per day most likely reflects potential savings in fuelwood attributable to the use of the FN cookstove as compared with traditional cooking systems. This is equivalent to an 11.6% decrease in fuelwood use.

Comparison and analysis of test results

The thermal efficiency of the FN stove} based on WBT results indicates that this cooking device has the potential to transfer 15% of the energy released during fuelwood combustion to the receptor. Assuming that the average thermal efficiency of a traditional three-stone fire is about 10%, then the FN stove is 33% more efficient than the traditional three-stone fire, meaning that for every kilogram fuelwood used in the traditional three-stone fire to cook, the FN cookstove only needed 0.67 kg fuelwood to perform the same task.

This difference in thermal efficiency indicated by the WBT contrasts significantly, however, with the difference in SFC between the traditional three-stone fire and the FN cookstove indicated by the CCT (13.4%), attributable to the fact that four burners (100% installed capacity) were used in the WBT as compared with only two burners (50% installed capacity) in the CCT. Under these conditions, the concept of "economies of scale" could be applied to fuelwood consumption to the extent that the cookstove can be used at full capacity.

On the other hand, the average fuelwood savings achieved by the KPT as proxy indicator of cookstove efficiency only represents one-third of the thermal efficiency obtained with the WBT, apparently confirming the widespread assertion in the field of evaluation of cooking system efficiency: there is no correlation between the efficiency achieved under controlled conditions and that measured in actual field conditions using the KPT (Bailis et al., 2007; Lee et al., 2013). fuelwood savings was observed between the difference detected in SFC with the CCT (13.4%) and the difference in fuelwood consumption with the KPT (11.6%).

This similarity in results could be attributable to the semi-controlled conditions in which the CCT was conducted in the case of this study. Aspects related to cookstove use and type of fuelwood used were handled in a more flexible manner, similar to the way the KPT is managed and not the controlled way in which the test is normally performed. This similarity is only anecdotal as KPT results were inconclusive.

Conclusions

- The thermal efficiency of the improved wood-burning FN cookstove was 15%, calculated by averaging the results of the cold-start and hot-start phases in the WBT. Only 7% thermal efficiency was reached in the simmering phase. These values indicate a 33% improvement in fuelwood use as compared with the three-stone fire or traditional cookstove.

- The CCT performed by the 30 involving households indicates that thermal efficiency, expressed in terms of SFC, increased by 13.4% when the improved FN cookstove was used as compared with the three-stone fire or traditional cookstove.

- The 11.6% decrease in fuelwood consumption during the KPT is inconclusive because the study sample size (30 households) proved insufficient to demonstrate that data of average fuelwood consumption were statistically significant at the 95% confidence level. Given the scope of the present study, the effect of "suppressed demand" on the variability of results, particularly those presenting negative values, was not assessed. Based on this concept of "suppressed demand", any given household, restricted to using a certain amount of fuelwood and therefore probably unable to satisfy all its energy requirements for cooking prior to the introduction of the improved FN cookstove, would be able to satisfy its energy requirements with the new cookstove, at the expense of increased fuelwood consumption. A broader definition of this concept and case studies that further illustrate it can be found in Battye *et al.* (2011).

- The comparison of ex-ante/ex-post fuelwood consumption could have an adverse effect on analysis results in the case of households where the number of people fed at each meal varies noticeably from day to day basis during the testing period. Further assessments are required to study this aspect in detail and corroborate findings.

- Sampling size should be increased so results can positively corroborate or reject KPT data.

- No relationship was found between the theoretical decrease in fuelwood consumption obtained with the WBT and the decrease in consumption obtained by direct measurement in field with the KPT. Nor does there seem to be a relationship between WBT and CCT results although both tests are conducted under very similar conditions and, as a result, the decrease in fuelwood consumption, expressed in terms of thermal efficiency and SFC, should not vary significantly.

Further discussion is required on the convenience of using either method to determine the saving achieved in fuelwood use when an improved cookstove is introduced into a real cooking environment.

References

Adkins, E., Tylera, E., Wang, J., Siriri, D., Modi, W. (2010). Field testing and survey evaluation of household biomass cookstoves in rural sub-Saharan Africa. *Energy for Sustainable Development*, 14(3), 172–185.

Aristizabal, J. (2010). Estufas mejoradas y bancos de leña: Una alternativa de autoabastecimiento energético a nivel de finca para comunidades dependientes de los bosques de roble de la Cordillera Oriental. *Colombia Forestal*, 13(2), 245–256.

Bachmann, J. (2009). *Black carbon: A science/policy primer*. Arlington, VA: Pew Center on Global Climate Change. Retrieved from http://www.c2es.org/docUploads/black-carbon-12-16-09.pdf

Bailis, R. (2014). *Controlled Cooking Test [on line]. Version 2*. Retrieved from http://ehs.sph.berkeley.edu/hem/content/CCT_Version_2.0_with_appendix5_Aug2004a.

Bailis, R, Berrueta,V., Chengappa,C., Dutta, K., Edwards, R., Masera, O., Still, D., Smith K.R. (2007). Performance testing for monitoring improved biomass stove interventions: Experiences of the Household Energy and Health Project. *Energy for Sustainable development*, 11(2), 57–70. ISSN 0973-0826

Bailis, R., Kirk, R., and Rufus E. (2014). *Kitchen Performance Test*. Retrieved from http://ehs.sph.berkeley.edu/hem/content/KPT_Version_3.0_Jan2007a.pdf.

Battye, W., Gavaldão, M., Grapeloup, M., and Yann F.Y. (2011). *Suppressed demand and the carbon markets: Does development have to become dirty before it qualifies to become clean?* Aubagne (France): GERES–CDC Climate. Retrieved from http://www.geres.eu/images/publications/a-report-suppresseddemand.pdf

Bryden, M. (2005). *Design principles for wood burning cookstoves*. Cottage Grove, OR (USA): Aprovecho Research Center. Retrieved from ///C:/Users/andrea/Downloads/principles-wbcs.pdf

Colombia. Ministerio de Ambiente, Vivienda y Desarrollo Territorial. (2007). *Inventario nacional de fuentes y liberaciones de dioxinas y furanos en Colombia: Línea base 2002*. Bogotá: MinAmbiente–GEF–BM–UNDP. ISBN 978-958-97978-5-3.

Departamento Nacional de Estadística (DANE). (2009). *Encuesta de Calidad de Vida 2008. Bogotá: DANE, Anexo, cuadro 14 (archivo Excel)*. Retrieved from http://www.dane.gov.co/index.php?option=com_content&view=article&id=487&Itemid=66

DeFoort, M., DeFoort, C., L'Orange y Kreutzer, C. (2014). *Stove Manufacturers Emissions & Performance Test Protocol (EPTP)*. Retrieved from http://cleancookstoves.org/binary-data/DOCUMENT/file/000/000/73-1.pdf

Global Alliance for Clean Cookstoves. ISO (2014). *International Workshop Agreement: Guidance for clean cookstoves*. Retrieved from http://www.

vrac.iastate.edu/ethos/files/ethos2013/Lecture%20Hall/Saturday%20AM/Review%20of%20ISO%20International%20Workshop%20Agreement%20Cookstove%20Guidance.pdf.

Harvey, A. and Tomas, A. (2011). *Guidelines for field performance tests of energy saving devices and kitchen performance tests (FTs–KTs)*. Oxford (UK): Climate Care.

Kissinger, G. Herold, M., and De Sy, V. (2012). *Drivers of deforestation and forest degradation: A synthesis report for REDD + policymakers*. Vancouver: Lexeme Consulting. Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/66151/Drivers_of_deforestation_and_forest_degradation.pdf

Larsen, B. (2004). *Cost of environmental damage: A socio-economic and environmental health risk assessment. Final report.* Bogotá: Ministerio de Medio Ambiente, Vivienda y Desarrollo Territorial.

Lee, C.M., Chandler, C., Lazarus, M., and Johnson, F.X. (2013). *Assessing the climate impacts of cookstoves projects: Issues in emissions accounting*. Stockholm: Stockholm Environment Institute (SEI). Retrieved from http://sei-us.org/Publications_PDF/SEI-WP-2013-01-Cookstoves-Carbon-Markets.pdf

MacCarty, N., Still, D., Ogle , D., and Drouin, T. (2008). *Assessing cook stove performance: Field and lab studies of three rocket stoves comparing the open fire and traditional stoves in Tamil Nadu, India, on measures of time to cook, fuel use, total emissions, and indoor air pollution*. Cottage Grove, OR (USA): Aprovecho Research Center

The Water Boiling Test. Version 4.2.2. (2014). Retrieved from http://www.aprovecho.org/lab/pubs/testing.

World Health Organization. (2006). *Fuel for life*. Geneve: WHO. 42 p. ISBN 978-92-4-156316-1.