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Method for Determining the Combination of Parameters Allowing Us to Minimize $PM_{2.5}$ Emissions When Using an Eclaire-Tarru Cookstove

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Abstract: The aim of this paper is to determine the optimal level of use of an improved cook stove on $PM_{2.5}$ emissions. Four factors or variables (cook stove type, fuel type, initial combustion chamber load and ventilation) with two levels were studied. The statistical method Design Of Experimentation (DOE) allowed us to develop a plan for the tests to be carried out as analysis of variance (ANOVA) is used in the discussion of the results. $PM_{2.5}$ emissions are therefore only significant during the boiling phase. In order to minimize them, you must use the "Eclair-taaru"1 cook stove (with secondary air inlet holes) and a minimum load. The other factors (fuel type and ventilation) can be used at desired levels. We also see that secondary air therefore has a positive effect on reducing $PM_{2.5}$ emissions.

Keywords: Biomass combustion; Charcoal stove; Water boiling test; $PM_{2.5}$ emission; ANOVA.

1. Introduction

In recent years, there has been a major interest in the study of stoves and solid fuels by NGOs and scientists. Most of the studies have focused on improving the quality of biomass cook stoves [1], reducing solid fuel consumption [2], improving stove performance [3], [4] as well as on the reduction of emissions (CO_2, CO and $PM_{2.5}$) [5] [6].

The adoption of these improved stoves is timid in Africa and a large part of the population still uses traditional stoves, exposing a certain segment of the population to pollution. Exposure to air pollution emitted by cook stoves doubles the risk of childhood pneumonia and acute lower respiratory tract infections of children [7]. It can also cause cardiovascular diseases, infanto-juvenile pneumonia, eye diseases, asthma… [8]. Particles of matter with diameter smaller than 2.5 µm ($PM_{2.5}$) are the most dangerous pollutant fraction for human health. The highest concentrations of fine particles ($PM_{2.5}$) are, however, observed in the intertropical regions and particularly in Africa [9]. In Sub-Saharan Africa, the levels of particles emitted by the combustion of solid biomass with traditional stoves is 3000 $\mu g/m^3$ in a hut with a traditional stove (tree-stone fire) [7]. This concentration is approximately ten to fifty times higher than the values advised by the World Health Organization (WHO) [5]. For World Health Organization (WHO) and the Institut de Veille Sanitaire (INVS) in France, particles of matter ($PM_{2.5}$,) are responsible for 7 million premature deaths worldwide each year [10]. In Africa, this number is about 1.1 million deaths each year [11]. Given that about 80% of the population in Africa still cooks with biomass, there is therefore a need to find ways and techniques to reduce these emissions of $PM_{2.5}$ particles as much as possible.

In order to make our contribution in the sector of improved stoves, we propose in this paper a technique who would optimize the emissions of $PM_{2.5}$ while using charcoal cook stove.
The Design Of experimentation method is the one adapted to study the effect of a parameter or a combination of parameters on a desired response [12]. Four parameters (cook stove type, fuel type, initial combustion chamber load and ventilation) were chosen to study their effect on $PM_{2.5}$ emissions during water boiling tests. The results obtained are analyzed and interpreted by the analysis of variance (ANOVA). During the boiling phase, the factors (cook stove type and initial load) have significant effects on $PM_{2.5}$ emissions. On the other hand, during the simmering phase, no factor has a significant effect on emissions.
To reduce $PM_{2.5}$ emissions when using such a cook stove, the best combination of factors is the "Eclair taaru"1 stove with a minimum of initial combustion chamber load of charcoal (wood or typha) and with or without fan.

2. Materials and Methods

"Eclair Taaru" stove

Cooking with charcoal in Sub-Saharan Africa is typically performed with a simple stove usually made out of scrap sheet metal by local artisans generally named "Malgache" with no airflow control. With this stove, the pot sits directly on the charcoal bed and can block the air passage in combustion chamber [13].
The improved cook stove (ICS) selected for this study is a new innovative design of charcoal ICS developed by GIZ initially in Benin and Burkina Faso, called the “Éclair” referring to the fact that the device is faster than any other cook stove [14] and recently in Senegal, where it has been renamed "Éclair-Taaru". "Taaru" in local language means beautiful referring to the fact that the device take care of users’ health, economy and environment.
To make the difference between the stove with secondary air inlet and the stove without secondary air inlet, two stoves are considered in this study: "Éclair-Taaru"1 stove and "Éclair-Taaru"2 stove. That will limit the variability of certain factors.
The "Éclair-Taaru" (Figure 1) works as a "quasi-gasifier" with natural air convection. The stove is made from metal sheets and local tinsmiths are trained to manufacture the stoves. The air inlet compartment consists of two concentric cylinders acting as primary/secondary air separator to separate flow passage of two combustion airs. Very few charcoal stoves have a secondary air controller. Primary air enters through a side door which can also be opened and close to regulate airflow. Inflow of primary air supplies the charcoal in the combustion chamber from underneath. Provision of primary/secondary air separator allows secondary air to enter from the bottom holes of the outer cylinder and to get heated and rise upward towards combustion chamber at of just above the top level of the burning fuel. Preheated secondary air between the metal walls is then mixed with existing volatile contents efficiently to ensure complete combustion. Primary and secondary airflow can be driven externally by a fan or blower. To avoid variations due to the change of cook stove, we have simply blocked the secondary air holes with the Scotch (or Duktape) that give us "Éclair-Taaru"2 stove (Figure1b) without secondary air.

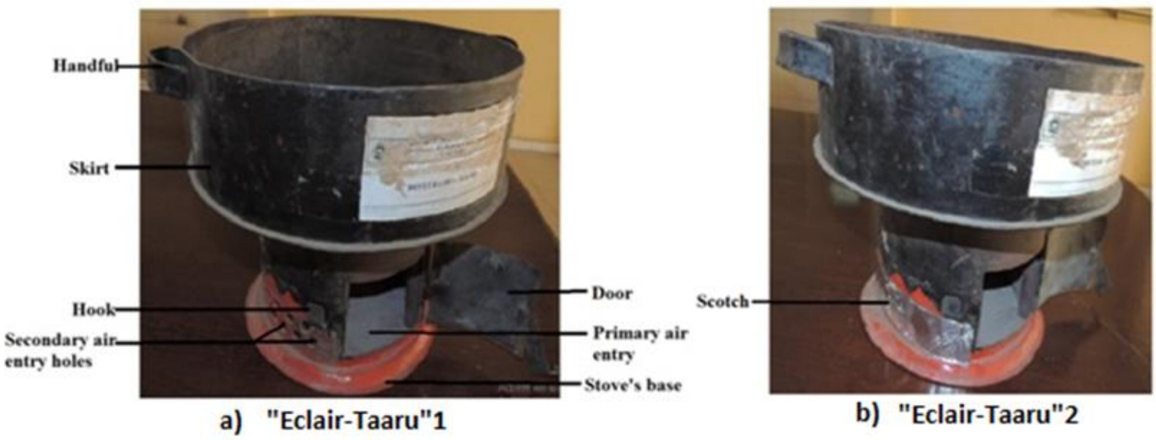

Figure 1: Pictorial view of the improved "Éclair-Taaru" charcoal cooking stove.

Fuels used

The stoves were tested with two different fuel types: natural wood charcoal and typha lump charcoal (figure 2). Wood charcoal is bought in Dakar local market and come from South and/or East Senegal by using many different wood trees. For the typha lump charcoal, it's produced in North of Senegal (Saint Louis) by family business. Wood charcoal in Senegal is produced by carbonizing wood in a low-oxygen atmosphere using traditional or improved Casamance kiln and can be purchased at the local market. The gathered charcoal consisted of a combination of thin and thick pieces randomly distributed. Typha lump charcoal obtained through agglo-briquetting, from invasive typha australis are produced in a process combining carbonization in kilns and agglomeration. The briquettes can have additives such as clay or molasses as binding agent. Typha lump charcoal used in this work have round forms. Indeed, it has been proven by other researchers that variations in fuel dimensions have little influence and sometimes do not even affect the results on emissions and performance of cook stove. The effects of the size of wood fuel on efficiency and emission of the stoves were investigated. The fuel size had no significant influence on the efficiency of the stove. It was observed that the burn rate increased as the size of fuel decreased. Burn rate can be regarded as comparable to firepower. It has been reported that with increasing firepower, stove efficiency generally tends to reduce, as more energy is lost to the surroundings rather than transferred to the pot [15]. The properties of the two fuel types are shown in table 1.

Figure 2: Fuels used in the tests.

Table 1: Fuels characteristics

Fuels	**Moisture mass fraction (%)**	**Volatile Mater (%)**	**Ash (%)**	**Fixed Carbon (%)**	**HCV (J/kg)**
Wood Charcoal	5.05	39.94	7.05	53.01	27509.59×10^3
Typha lump charcoal	5.66	52.95	43.22	3.83	15479.13×10^3

Water boiling test (WBT) protocol

The WBT protocol "Version 4.2.2. (2013)" was used to determine cook stove power, energy efficiency and emissions (CO, CO_2 and PM). It is an internationally well-known and defined protocol that can be used to test and compare any cook stove in the field and in laboratory. This allows any WBT results from any laboratory to be compared with those from other laboratories regardless of the stoves used. However, WBT is a simulation of actual cooking activities in communities. The WBT consists of three components: the high-power cold-start (1), the high-power hot-start (2) and the low power or simmer simulate the slow cooking step (3). The same initial charge is used for boiling and simmering water throughout the test, no other fuel is added. Thermal efficiency and emissions data were collected only for high-power cold start and low power. The hot start was omitted to save testing time. In the high-power cold start the test begins with the cook stove, pot and water at ambient temperature and uses a pre-weighed amount of charcoal to boil 5 liters of water in a standard pot. The low-power simmering phase continues immediately from the cold start and is used to simmer water 3°C below boiling temperature for 45 min. For stove with a door to control air supply, the door was kept open for high-power cold start test and closed during low power test.

Experimental design and statistical analysis

The experimental design for the study consisted of four factors (or independents variables): cook stove type (traditional stove, improve cook stove), fuel type (lump charcoal, briquettes), fuel initial load (maximum load, minimal load) and ventilation (with ventilation, without ventilation); each with two levels denoted by ("low (-1)" and "high (+1)"). Independent variable and their levels are presented in table 2. Analysis of variance (ANOVA) with Fisher's statistical test (F-test) was applied to ascertain statistically significant difference in average values of factors and their interaction at a confidence level of 95 % [16]. Further, the Newman-Keuls test was conducted in order to identify factors means that are significantly different from each other.

Table 3: Independent variables and their levels used in the experimental design

Response	Factors and coded	Levels and values	
		High (+)	**Low (-)**
	Stove type (X_1)	"Eclair taaru" 1 (X_{+1})	"Eclair taaru" 2 (X_{-1})
	Fuel type (X_2)	Wood Charcoal (X_{+2})	Typha Charcoal (X_{-2})
Y_{em} : $PM_{2.5}$ Emission	Fuel initial load (X_3)	730 g Filled on board (X_{+3})	500 g (Filled under the holes : X_{-3})
		1000 g (Filled on board) (X_{+3})	730 g (filled under the holes: X_{-3})
	Fan (X_4)	With fan (X_{+4})	Without fan (X_{-4})

A general linear interaction model equation (1) which accounts for the main effect of factor with their interaction effects was considered in this study [17], [18].

Usually, two values (called levels) of the X's are used in the experiment for each factor. The response functions measured were emission Y_{em}. The responses were related to coded value (X_i) by linear interaction model shown in equation 1.

$$\mathbf{Y_{em} = \beta_o + \sum_{i=1}^{4} \beta_i X_i + \sum_{i=1}^{4}\sum_{j=1}^{4} \beta_{ij}X_iX_j + \sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{k=1}^{4} \beta_{ijk}X_iX_jX_k + \beta_{ijkl}X_iX_jX_kX_l + \varepsilon_{m(ijkl)}} \quad (1)$$

with: I ≠ j; I ≠ k; j ≠ k

where,

Y_{em}: is the predicted response of the process ($PM_{2.5}$ emissions)

β_o= the overall mean response,

β_i = the main effect for factors (i=1,2,3,4)

β_{ij}= the two-way interaction between the ith and the jth factors,

β_{ijk}= the three-way interaction between the ith,jth,and kth factors

β_{ijkl}= the four-way interaction between the ith,jth,kth,and lth factors.

$^{\varepsilon}m_{(ijkl)}$: is an experimental error which is due to different variations of the environment or uncontrollable variables.

3. Results & Discussion

Results

A fractional factorial design was developed with two levels and 4 factors [12]. The test results are shown in Table 4. These results on the 24 tests are obtained with the LEMS (Laboratory Emissions Monitoring System) software.

Table 4: Water boiling tests results.

Runs	Combination order	$PM_{2.5}$ Emissions (g/kg)	
		Boiling phase	**Simmer phase**
1	(1)	0.13	0.30
2	X_2X_4	0.01	0.00

3	X_1X_3	0.07	0.06
4	X_1X_2	0.00	0.00
5	X_2X_3	0.02	0.00
6	$X_1X_2X_3X_4$	0.29	0.00
7	X_3X_4	0.26	0.13
8	X_2X_4	0.01	0.00
9	X_2X_4	0.00	0.00
10	$X_1X_2X_3X_4$	0.05	0.01
11	X_3X_4	0.53	0.19
12	X_1X_4	0.18	0.04
13	(1)	0.42	0.07
14	X_2X_3	0.49	0.31
15	X_1X_3	0.09	0.12
16	X_2X_3	0.08	0.05
17	(1)	0.00	0.00
18	X_1X_4	0.06	0.07
19	X_1X_3	0.06	0.16
20	X_1X_2	0.00	0.00
21	$X_1X_2X_3X_4$	0.02	0.00
22	X_3X_4	0.73	0.05
23	X_1X_4	0.07	0.11
24	X_1X_2	0.00	0.00

Discussions

ANOVA $PM_{2.5}$ emissions during the boiling phase

Particles of matter with a diameter of less than 2.5 micrometers ($PM_{2.5}$) are produced during the combustion of solid biomass and are capable of reaching deep into the lungs causing respiratory diseases such as: asthma, infections acute respiratory illnesses, chronic bronchitis etc. [19]. Table 5 presents the ANOVA of $PM_{2.5}$ during the boiling phase.

Table 5: ANOVA $PM_{2.5}$ emissions during boiling phase.

Sources	Degree of Freedom	*Alias*	Sum of Squares	Mean of Squares	F-value	F-Critical
X_1	1	$X_2X_3X_4$	0.1335	0.1335	5.16	4.54
X_2	1	$X_1X_3X_4$	0.1107	0.1107	4.28	4.54
X_3	1	$X_1X_2X_4$	0.1365	0.1365	5.28	4.54
X_4	1	$X_1X_2X_3$	0.0301	0.0301	1.16	4.54
X_1X_2	1	X_3X_4	0.0693	0.0693	2.68	4.54
X_1X_3	1	X_2X_4	0.0672	0.0672	2.60	4.54
X_1X_4	1	X_2X_3	0.0001	0.0001	0.00	4.54
$X_1X_2X_3X_4$	1	(1)	0.0000	0.0000	0.00	4.54
ERROR	15		0.3878	0.0259		
TOTAL	23		0.9353			

During the boiling phase, ANOVA table 5 shows that the factor X_1 (cook stove type) and the factor X_3 (initial load) have a significant effect on $PM_{2.5}$ emissions. Other factors and combinations of factors have no significant effect on $PM_{2.5}$ emissions. To better judge the origin of the effect of each factor, we use the table of average levels of factors following Table 6.

Table 6: Optimal levels of $PM_{2.5}$ emissions during boiling phase.

Factors	Factors levels	Main (g/kg)
X_1 : Stove type	"Eclair taaru" 2	0.074
	"Eclair taaru" 1	0.223
X_3 : Initial load	Minimum load	0.073
	Maximum load	0.224

The difference between the two factors levels is very significant and the level that produces few $PM_{2.5}$ emissions is the one that will be used. So, to minimize $PM_{2.5}$ emissions, the "Eclair-taaru 1" cook stove is used with a minimum fuel load with any of the 2 fuels and with or without ventilation.

ANOVA PM2.5 emissions during the simmer phase

Table 7 presents the ANOVA of particulate matter emissions ($PM_{2.5}$) during the simmering phase.

Table 7: ANOVA $PM_{2.5}$ emissions during simmering phase.

Sources	Degree of Freedom	*Alias*	Sum of Squares	Mean of Squares	F-value	F-Critical
X_1	1	$X_2X_3X_4$	0.0117	0.0117	1.44	4.54
X_2	1	$X_1X_3X_4$	0.0360	0.0360	4.43	4.54
X_3	1	$X_1X_2X_4$	0.0100	0.0100	1.23	4.54
X_4	1	$X_1X_2X_3$	0.0092	0.0092	1.13	4.54
X_1X_2	1	X_3X_4	0.0012	0.0012	0.15	4.54
X_1X_3	1	X_2X_4	0.0022	0.0022	0.27	4.54
X_1X_4	1	X_2X_3	0.0026	0.0026	0.32	4.54
$X_1X_2X_3X_4$	1	(1)	0.0000	0.0000	0.00	4.54
ERREUR	15		0.1221	0.0081		
TOTAL	23		0.1951			

At the level of this table (table 7), the finding is that no main factor or combination of factors has a significant effect on $PM_{2.5}$ emissions during the simmering phase. Only the postman X_2 presents the largest effect but which remains lower than 4.54 so it is not significant on $PM_{2.5}$ emissions. In such scenario, all combinations are good and none is better or worse than the other. This seems to be logical because it is with the coal embers (used to boil the water) that we continue the simmering. There is no additional fuel added. On the other hand, emissions are considerable at the start of combustion.

Finally, here is presented in Table 8 the best combinations that will minimize $PM_{2.5}$ emissions when using this fireplace.

Table 8: Recapitulation of optimal parameters which gives us best results.

Reponses	Optimal parameters			
Boiling phase	"Eclair taaru" 2	Wood or typha charcoal	Minimum load	With or Without fan
Simmer phase	"Eclair taaru" 2 or "Eclair taaru" 1	Wood or typha charcoal	Maximum or minimum load	With or Without fan

This table allows us to see that to minimize $PM_{2.5}$ emissions, it is necessary to use the "Eclair taaru" 1 stove (with secondary air holes) with a minimum load of charcoal (wood or typha) with or without ventilation.

In order to confirm this combination of factors, three validation tests are carried out. To better appreciate the results of the validation tests, a confidence interval has been developed outside of which no result is good. The following relation [20] makes it possible to find each confidence interval.

$$\overline{Y_{ji}} \pm t_{1-\frac{\alpha}{2}} \sqrt{\frac{MC_{erreur\ i}}{n_j}}$$

Where:

MCerror is the mean square of the error of the sought objective.

n_j = 3, number of times the combination is used in the experimental design.
$t_{1-\frac{\alpha}{2}} = t_{0.975}$ = 2.131 with dof = 15. It is determined using the Student distribution with 15 degrees of freedom with α = 0.05.
$\overline{Y_{ji}}$: The average of the results of the "Eclair taaru" 1 stove combination, charcoal, minimum load with the ventilation for each objective. Table 9 presents the confidence intervals and the 10 the results of validation.

Table 9: Table of validation limited.

Objective	Low level	Upper level
Boiling phase	0.00	0.20
Simmer phase	0.00	0.11

Table 10: Validation tests results.

Objective	V1	V2	V3	Mains
Boiling phase	0.01	0.02	0.01	0.01
Simmer phase	0.00	0.01	0.00	0.003

The results of the validation tests in table 10 remain within the previously determined confidence interval. This makes it possible to confirm the combination obtained and which makes it possible to minimize $PM_{2.5}$ emissions.

5. Conclusion

The solid biomass combustion (charcoal, wood, agricultural or forestry residues, or even ecological coal) emits a lot of gases containing fine particles including $PM_{2.5}$. These $PM_{2.5}$ particles have harmful effects on health. But the abandonment of the use of this solid fuel is not for today in many developing countries. So one of the solutions is to reduce these emissions during biomass combustion. Thus, several factors (variables) that could affect these $PM_{2.5}$ emissions were studied with two levels using the statistical method of Design of Experiment.
This method, coupled with ANOVA, allowed us to analyze the effecs of factors as well as the effects of interactions of factors on $PM_{2.5}$ emissions. A fractional factorial design of four factors (cook stove type, fuel type, initial fuel load and ventilation) was developed to extract maximum information from the tests.
The analysis and interpretation of the results on $PM_{2.5}$ emissions shows two factors (type of cook stove and initial load) with significant effects. Continuing the analysis shows that emissions are high with the "Eclair-taaru" 2 cook stove (without the secondary air holes) as well as with the maximum load during the water boiling phase.
On the other hand, during the simmering phase, no factor or combination of factors has a significant effect on $PM_{2.5}$ emissions.
So to minimize $PM_{2.5}$ emissions, you must use the "Eclair-taaru"1 cook stove with a minimum load, with the fuel of your choice as well as with or without ventilation.
On the other hand we can see that secondary air has a beneficial effect on the combustion of solid biomass.
New improved stove prototypes must secondary air holes.
In perspective, we will propose to carry out the same study on CO_2 emissions, or on CO emissions.

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