Influence of the constructive features of rocket stoves in their overall efficiency

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This contribution presents the results obtained from the cooking laboratory experiment, performed in the summer term 2016, included in the Postgraduate Programme of Renewable Energies (PPRE). The experiment was supervised by Dr. Herena Torio and to encourage students to investigate the performance of the so-called Improved Cooking Stoves, used in the rural areas of the developing countries around the world.

Cooking has become a challenge in areas where the energy access is limited and the single available fuel is wood. Day by day, more people have been reported with respiratory diseases, caused mainly by the smoke, carbon monoxide and other highly harmful compounds resulting from the poor combustion generated on the simplest stoves. Besides, the high timber consumption caused by the extremely low efficiency of open fires implies an extra pressure over a resource that in some areas is already scarce and consumes valuable time that could be used in other activities that can contribute to improve the quality of life.

The improved cooking stoves have been presented as the solution and, in fact, they have contributed to a great extent solving the problems with the traditional open fire. Nevertheless, it has been seen that these stoves, specifically the rocket stoves report efficiencies below 20%. This fundamental aspect catches the attention and helps to call on the fact that much more has to be done in this field.

Key words: Rocket stove, efficiency, water boiling test

Nomenclature

WBT	Water Boiling Test
c	Specific heat capacity of water
m^f_{water}	Remaining mass of water after the WBT
m^i_{water}	Initial mass of water before the WBT
ΔT	Change on water temperature during the WBT
ΔH_{vap}	Enthalpy of evaporation of water
$m_{wood,dry}$	Mass of the dry wood
$m_{wood,moist}$	Mass of the humid wood
c_m	Moisture content in the wood
SE	Standard error
SD	Standard deviation
N	Number of samples (measurements)
X_m	Mean value of the measurements
X_n	Each one of the measurements

1 Introduction

Cooking could be seen as a normal daily activity that usually does not take too much time or effort, and that rarely represents a health hazard. This could be the situation for people with a good standard of life and a reasonable monthly income, but for people living in areas where the resources are not easily available and the energy access is limited, cooking could be a challenge.

In many developing countries the most commonly used fuel is wood[1], the task includes walking long distances searching timber, chopping, cooking in an environment full of smoke, carbon monoxide and particulate pollution. It consumes the time that could be used on education or in other business that, in the end, can help the family to afford other less harmful cooking technologies.

On the other hand, in most cultures, cooking is a women's job. This fact increases the gender gap, mainly because it is the women who have to leave the school and dedicate their time to the house activities from which cooking represents in some cases up to 40%[2]. Hence, improving stoves' efficiency becomes not only a technical but also a social matter [3].

From the technical point of view, if the efficiency of the cooking stoves were increased, e.g. the consumption of wood would be considerably reduced, which could impact the quality of life of the people. In general, in order to improve the efficiency of the stove, the burning efficiency of the wood and the heat transfer efficiency into the food should increase. The impact of increasing the combustion efficiency is the reduction of harmful emissions. However, even though the combustion taking place within the stove is the cleanest that could be obtained, a poor heat transfer to the food would lead to a significant wood consumption [4].

2 Water boiling test – Experimental procedure and calculation of the stove efficiency

During the experiment, two stoves with different constructive features were used: stove No. 1 and stove No. 2. With these stoves the water-boiling test was done in order to calculate the efficiency of each stove and, afterwards, analyze which constructive features could have influenced the efficiency results for each stove. Furthermore, the features, which could have led to achieve a higher efficiency when the two stoves are compared, were wanted to be found as well. The dimensions for each stove are shown in figure 1. It is worth mentioning that two identical pots were used in each stove. The pot has a diameter of 20 cm and a height of 16.5 cm (Figure 2).

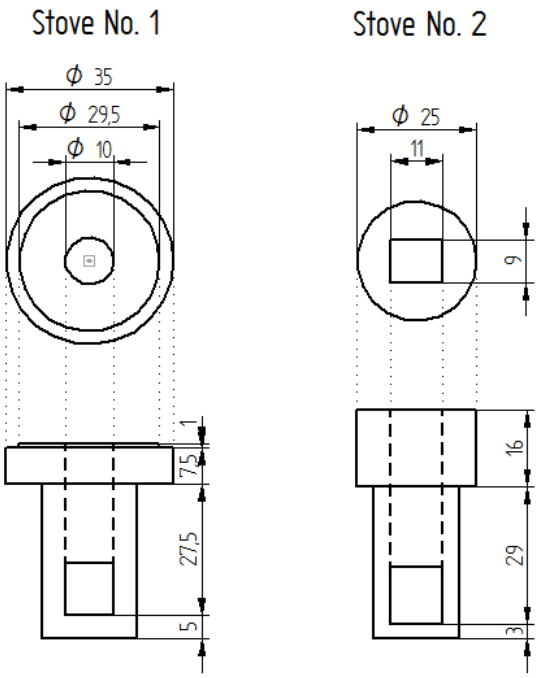

Figure 1. Dimensions of the stoves (measurements in centimeters)

Figure 2. Rocket stove No. 1, Rocket stove No. 2 and pot used during the experiment

The Water Boiling Test procedure was performed in order to obtain the information needed to estimate the efficiency for each stove[3].

In order to get comparable results, the same kind of wood, the same measurement instruments as well as the same type of pot were used.

First, the stove to be tested was cleaned, the pot was filled with a certain amount of water and its temperature, as well as its weight were measured. For both stoves, approximately 3 kg of water were used. Afterwards, the wood to be added was weighted.

The stove was turned on and the time until boiling was taken and the boiling temperature was recorded. More wood was added in order to maintain the same temperature during

30 min. The wood required, the remaining charcoal and the ashes were weight separately after finishing the test. It is worth to add that the wood required to turn on the stove was included in the calculation of the efficiency.

The temperature and the mass of the water after the test were measured and recorded to perform the following calculations. The same procedure was applied to test the second stove.

To determine the moisture content of the wood used during the experiment, a small piece with a known starting weight was placed in the oven at 91°C. The sample was left in the oven for 6 days to ensure the minimum humidity percentage on it. The sample was weighted and the measurement was recorded.

For the calculation of the efficiency, the heat transferred to the water and the heat released from the burning of the wood should be obtained. The efficiency of a stove can be calculated with the equation (1).

$$n = \frac{E_{water} - E_{steam}}{E_{heat}} \tag{1}$$

The energy stored in the remaining water mass after the experiment E_{water}, the energy used for the phase transition of part of the water into steam, E_{steam} and the energy released during the burning process E_{heat} can be obtained using the equations (2), (3) and (4) respectively. The properties of the water used for the calculations are c=4187 Jkg-1K-1 and ΔH_{vap}=2257 kJkg-1 [3]. On the other hand, during the experiment Birch wood was used as the fuel and it has a LHV_{wood}=16.6 MJkg-1 [5]. Finally, the used LHV for the charcoal was LHV_{char}=26.9 MJkg-1 [3].

$$E_{water} = c m^f_{water} \Delta T \tag{2}$$

$$E_{steam} = \Delta H_{vap}(m^i_{water} - m^f_{water}) \tag{3}$$

$$E_{heat} = (1 - c_m) LHV_{wood}(m^i_{wood} - m^f_{wood}) - LHV_{char} m_{char} \tag{4}$$

It is worth mentioning that with the aim of calculating the effective energy released in the burning process E_{heat}, the energy used for the evaporation of the moisture content c_m should be subtracted. This is reflected in the first term of the equation (4). For the calculation of c_m the equation (5) was used.

$$c_m = \frac{m_{wood,moist} - m_{wood,dry}}{m_{wood,moist}} \tag{5}$$

A piece of Birch wood was weighed at the beginning of the experiment to obtain $m_{wood,moist}$ and subsequently was placed in an oven for 6 days in order to remove all the moisture obtaining $m_{wood,dry}$. The values obtained at this stage are $m_{wood,moist}$ = 0.0414 kg and $m_{wood,dry}$ = 0.0394 kg, and the calculated moisture content is c_m=0.048.

The data obtained during the experiment and the resulting efficiency for each stove are shown in Table 1. As can be seen, the efficiency for stove No. 2 is higher than the efficiency for stove No. 1.

Measured Parameters	Stove No. 1	Stove No. 2
Ti water - (ºC)	23	18
Tf water - (ºC)	95	95
mi water - (kg)	3.46	2.97
mf water - (kg)	2.29	1.78
mi wood - (kg)	1.39	1.29
mf Wood - (kg)	0.12	0.02
m charcoal - (kg)	0.01	0.07
Efficiency – (%)	16.9	18.2

Table 1. Measured parameters and resulting efficiency for each one of the stoves

3 Influence of the geometry of the rocket stoves in the efficiency

In the literature, there is not much information about standards for the sizing of rocket stoves in order to improve the efficiency. Since this is a technology mostly used in rural areas, the information available shows empirical suggestion for each dimension of the constructive features of the stoves rather than scientific design criteria [4] [6]. Therefore, a comparison between the suggested dimensions from the literature and the dimensions for the rocket stoves used during the experiment is carried out, it has the aim to find out which possible constructive features could have had an influence in the results for the efficiency obtained for each stove.

Regarding the dimensions of the feeding entrance of the wood, the literature says it should be tight enough to keep the gases generated from the combustion inside the stove, but it should also be wide enough to allow sufficient draft to achieve the cleanest combustion possible [4]. Furthermore, the dimension of this feeding entrance is closely related to the dimensions of the combustion chamber of the stoves. Literature suggests that the combustion chamber should have approximately the same cross section area or a bigger cross section area than the feeding entrance in order to avoid bottlenecks inside the stove that would affect the draft, the flow of the gasses or would cause back up smoke that would escape through the feeding entrance [6].

The area of the feeding entrance and the combustion chamber were calculated for both stoves (Table 2). As it can be seen from the results, the area of the feeding entrance of stove No. 1 is 21% bigger than the area of stove No. 2. On the other hand, the area of the combustion chamber of stove No. 1 is half of the area of its feeding entrance, whereas the area of the combustion chamber of stove No. 2 is 3/4 of the area of its own feeding entrance. Consequently, the dimensions of the feeding entrances and the combustion chamber of stove No. 1 are the ones that are farther from what is suggested in the literature, and could be possible causes that contribute to the lower efficiency compared with stove No. 2. This is mainly because a poor draft and a lower flow of gasses to the pot could affect the combustion efficiency and the heat transfer efficiency, resulting in a higher consumption of wood. Effectively, the wood consumption of stove No. 1 is larger than the wood consumption for stove No. 2. It is worth mentioning that the wood was fed into the stove in different loads, the mass of the wood fed to the stove in each loads is shown in Table 3.

	Stove No. 1	Stove No. 2	Comparison between the feeding entrance areas.
Area feeding entrance (m^2)	$A_{ent.\_stove1}$= 0.016	$A_{ent.\_stove2}$= 0.013	$A_{ent.\_stove1} > A_{ent.\_stove2}$ (by 21%)
Area of the combustion chamber (m^2)	$A_{comb.\_stove1}$= 0.008	$A_{comb.\_stove2}$= 0.010	
Comparison between the feeding entrance area and the area of the combustion chamber.	$A_{comb.\_stove1} \approx 0.5 A_{ent.\_stove1}$	$A_{comb.\_stove2} \approx 3/4 A_{ent.\_stove2}$	

Table 2. Areas for the feeding entrance and the combustion chamber for both of the stoves

	Stove No. 1	Stove No. 2
Load No. 1 - (g)	54.6	6
Load No. 2 - (g)	2.9	0.4
Load No. 3 - (g)	533.4	67.8
Load No. 4 - (g)	803	451.6
Load No. 5 - (g)	-	763.8
Total mass - (g)	1393.9	1289.6

Table 3. Mass of wood fed into each one of the stoves

Regarding the combustion chamber, it is recommended to have a height three times bigger than its diameter [4]. For stove No. 1 this is accomplished since the diameter of the combustion chamber is 10 cm and its height is 27.5 cm. It is worth mentioning that it is assumed that a deviation of 2.5 cm, from the 30 cm height that the combustion chamber would have according to the literature, is not going to impact significantly the results for the efficiency. For stove No. 2, since its cross section is rectangular, the longest side of 11 cm was the one used for assessing the height. According to the recommendations, the height of the combustion chamber of stove No. 2 should be 33 cm. As can be seen in Figure 1, the actual height from the combustion chamber is 29 cm having a deviation of 4 cm. Actually, according to the empirical suggestions it is better to have a short combustion chamber above the fire since it will bring hotter gasses to the pot improving the heat transfer efficiency. In consequence, this feature could contribute to the higher efficiency of the stove No. 2.

One of the most common strategies used to improve heat transfer efficiency is the utilization of a skirt. The skirt is a metallic structure that surrounds the pot and allows the flow of hot air as close to the pot´s surface as possible, enhancing the contact and therefore the heat transfer efficiency. Its use is highly recommended basically because air is not an optimum medium for heat transfer [4].

The gap of each one of the stoves was measured, and while the gap in stove No. 1 represents 25% of the stoves useful contact surface; the gap in stove No. 2 represents 10%. From this fact, is evident that this difference will end up in a lower fuel efficiency on stove No 1, as it is shown in the results presented in Table 1.

Gap between skirt and pot

Pot diameter (mm)	Stove 1 diameter (mm)	Gap (mm)	(Gap %) From the stove diameter	Stove2 diameter (mm)	Gap (mm)	(Gap %) From the stove diameter
200	400	100	25	250	25	10

Table 4.Gap calculation

The only way to avoid this effect is decreasing the size of the gap and consequently increasing the contact area by using a wider pot in case of stove No 1. It is also worth to mention that a gap of 13mm is recommended as a rule of thumb for stoves that consume around 1.5 kg of wood per hour [4]. That is roughly this case. Therefore, reducing the gap in both cases would lead to a better performance.

On the other hand, the height of the skirt has also a big influence in the effective heat transfer, mainly because it affects the speed of the hot gases that scrape against the pot. A boundary layer of still air is formed on the pot surface, slowing down the heat transfer process. Then, a higher skirt will lead to higher speeds and better performance [4] .

For stove No. 1, the height of the skirt represents 45.5% of the total height of the pot, whereas for stove No. 2 this value reaches 97%. It is clear that the most convenient setup is again the one that uses stove No. 2.

The statements mentioned above, could lead to the hypothesis that with a pot that fits the gap as well as the height of the stove´s skirt; stove No. 1 could have a higher efficiency than stove No. 2, due to it has a bigger effective heat transfer area between pot and stove. This could be an argument to be explored by future groups.

4 Conclusion

In order to find out the influence of the dimensions of the stoves in their efficiency, the area of the feeding entrance, the area of the combustion chamber, the height of the upper skirt and the gap between the pot and upper skirt of the stoves were analyzed. As it can be seen from the comparison between the suggestions of the literature and the dimensions of the rocket stoves used during the experiment, in general, the dimensions of stove No. 2 are closer to the empirical recommendations found in the literature and possibly this is the reason why it has a higher efficiency than stove No.1.

Specifically, the area of the combustion chamber of stove No.1 is half of the area of its feeding entrance, which could possibly lead to bottlenecks for the draft and the combustions gases, which would affect the combustion and the heat transfer efficiency to the top.

On the other hand, regarding the height of the combustion chamber of both stoves, it can be seen that both follow the literature suggestions. Nevertheless, the stove No.2 has a shorter combustion chamber, which could improve the heat transfer efficiency to the pot. Hence, it can be inferred that the height of stove No. 2 could contribute to its higher efficiency in comparison with stove No. 1.

Finally, regarding the gap and the skirts height, for stove No. 2 it has been found that it has the gap that is closer to the one suggested by the literature and its skirt covers 97% of the pot height, representing better geometrical characteristics. This was reflected in the better performance observed for stove No. 2 compared with stove No. 1.

With a pot that fits the gap as well as the height of the stove´s skirt; stove No. 1 could have a higher efficiency than stove No. 2, due to its bigger effective heat transfer surface between pot and stove. This could be explored by future groups.

The efficiency of the rocket stoves was reported below 20% that means considerable effort is required in order to improve this aspect on the already improved cooking stoves.

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