# Operating and Performance Characteristics of Conical Grate Rice Hull Stoves


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## BACKGROUND:

Household cooking is one of the most important energy issues in rural areas of the Philippines. The vast majority of rural Filipino households still rely on traditional fuels for cooking, which include firewood, and charcoal. These biofuels are often cooked in simple clay stoves or more commonly a crude stove constructed of steel bars placed over bricks. Chimneys are often absent or poorly designed. The incomplete combustion of biomass can produce CO, $SO_2$, $NO_x$, fluorine, suspended particulate matter, and other harmful products. Within the home, these compounds are often many times more concentrated than health standards recommend, and can exceed pollution levels of the most polluted industrial cities. Additionally, intensive fuel wood and charcoal production contributes to ecological deterioration when unsustainably harvested.

In urban communities, LPG is the fuel of choice. Although LPG is clean burning and easy to use, it is expensive and represents a large percentage of a family's monthly budget. Displacing part of their LPG with rice hull is therefore an economically attractive option for urban families.

Rice Hull Stoves are a low cost alternative to current cooking methods, which substitute conventional cooking fuel with the use of abundant crop residues (i.e. rice hulls, coffee shells, coconut husks, etc). By utilising these crop residues families can reduce the amount of firewood, charcoal and LPG burned, which subsequently: increases household income; improves household air quality; reduces the firewood-collecting burden on women; and reduces greenhouse gas emissions.

## OBJECTIVES:

The general objective of this experiment is to compare operating characteristics of three conical grate rice hull stoves. The stoves to be tested are a) The Mayon Turbo Stove 6500 with a 60º hopper, b)The Mayon Turbo Stove 6500 with a 50º hopper and c) The CPU Conical Grate Rice Hull Stove.

Specific objectives are:

1. To evaluate the "usability" of the stoves. Five criteria will be used to quantify "usability":
    a. Start up time
    b. Frequency of smoke events
    c. Frequency of fuel bed fires
    d. Frequency of fuel delivery
    e. Boiling time
2. To evaluate the performance characteristics of the stove. Four criteria will be used to quantify performance:
    a. Average flame temperature
    b. % Ash/char produced
    c. Fuel consumption rate
    d. Overall efficiency (= energy delivered to pot / energy of fuel)

## METHODOLOGY AND PROCEDURE:

In order to achieve the maximum performance and minimize variability, one skilled stove user will operate the stoves during the entire experiment. Two other people will observe operational characteristics and record data during operation.

Three identical pots will be filled with equal amounts of water (approximately 1 liter) and placed on each of the stoves. The energy delivered to each pot will be determined from the change in water temperature from start-up to boiling, as well as from the weight of water evaporated during boiling.

Flame temperature will be taken directly below the pot, approximately every 2 minutes with a thermocouple. Average flame temperature will be calculated for each stove. Ash/char from combustion material will be collected, weighed and compared to the fuel consumed.

Fuel delivered and ash produced can be measured and used to determine energy available in the fuel. By knowing the Lower Heating Value (LHV) of rice hull and measuring the mass of fuel consumed during the burn, the amount of energy consumed by the MTS can be determined.

The overall efficiency will be calculated by dividing the energy delivered to the pot by the energy available in the fuel.

## APPARATUS & EQUIMENT:

The experiment was conduced inside the CPURE office building on June 25, 2003. The stoves were placed one meter apart on the office floor where wind drafts would be minimized. Each stove had a corresponding: pre-weighted rice hull sack; cooking pot with one liter of water; ash pan; and ash bucket.

- Thermocouple and digital display
- Mercury thermometer
- Digital scale
- Three pots without lids
- Rice hull sacks
- Ash pan
- Rice Hull Stoves
- Kestral 3000 Anometer
- Ash buckets

***Figure 1: MTS Experiment conducted at CPURE on June 25, 2003***

***Figure 2: Mayon Turbo Stove with 50º Hopper (stove model #1)***

***Figure 3: Mayon Turbo Stove with 60º Hopper (stove model #2)***

***Figure 4: CPU Conical Grate Rice Hull Stove (stove model #3)***

## STOVE DESCRIPTIONS

*A. Stove #1 – Mayon Turbo Stove with 50º Outer Hopper (Figure 2)*

The inner cone is constructed out of stainless steel, stands 7" in height, and contains two rows of 3/8" holes for secondary combustion. The outer hopper is made of 18 gauge black iron placed at a 50º angle; it contains three rows of 3/8" holes at the bottom of the hopper. The outer cylindrical cover is surrounded by a heat shield 13.2 cm high (which was added to prevent fuelbed fires) Two airjets 1" in diameter extend from the ashpan and are cut at 45º angles. The airjets supply air to the primary combustion area. An ashpan, with 4.75" diameter, is located 1.125" from the base of the outer hopper and is attached to the outer hopper by two small metal clips. The ashpan also has two 3/8" holes placed perpendicular to the jets. The potholder is a double-ring design fastened to the middle cylindrical cover by means of three 6mm round bars. Three legs, made from 10mm plain round bar, are used to support the stove. The overall height of the stove is 38 cm.

*B. Stove #2 - Mayon Turbo Stove with 60º Outer Hopper (Figure 3)*

This model is the current model being fabricated for commercial sale. The design parameters are the same as for Stove #1 (described above) however the angle of the hopper is 60º and the height of the inner cone is 6.375". The overall height of the stove is slightly shorter than Stove #1 standing at 37 cm.

*C. Stove #3 – Central Philippine University Conical Grade Rice Hull Stove (Figure 4)*

This conical-grade stove is made from a 18-20 gauge black iron steel sheet. Its outer hopper is placed at a 45º angle, with four rows of 5 mm holes at its base for perforation. The potholder consists of a circular ring with 3 prongs fastened to the outer cylindrical cover by 3 round bars; these three round bars additionally fasten the outer cylindrical cover to the outer hopper. The ashpan is fastened to the outer hopper and contains one airjet of 1.5" diameter. A fuel delivery lever is also attached to the ashpan (which is used to remove ash/char during the combustion process). The stove is supported by three legs made of plain round bars and is further supported by an additional three plain round bars placed perpendicular to the legs of the stove connecting them. This model contains no heat shield or holes for secondary combustion in the inner cone, however, the ashpan lever makes this stove unique compared to both Mayon Turbo Stove designs.

***Table 1. Dimensions of three conical-grade stoves; Mayon Turbo Stove 50º, Mayon Turbo Stove 60º; and Central Philippine University Conical Grade Rice Hull Stove.***

| **Stove** | **# 1 (MTS-50°)** | **# 2 (MTS-60°)** | **# 3 (CPU)** |
|---|---|---|---|
| Angle of Hopper | 50º | 60º | 45º |
| Diameter of Outer Hoper (Top/Bottom) | 16.75" / 4.3125" | 14.125" / 4.3125" | 15.75" / 2.75" |
| Height of Inner Cone (Frustrum) | 7" | 6.25" | 5.25" |
| Height of Main Drum | 6.375" | 6.375" | 7.0625" |
| Height of Heat Shield | 5.2" | 5.2" | N/A |
| # of Perforations | 76 (in 3 rows) | 76 (in 3 rows) | 124 (in 4 rows) |
| Diameter of Perforations | 3/8" | 3/8" | 3/16" |
| Height of Potholder from Cylinder[1] | 1.375" | 1.0625" | 0.75" |
| # of Secondary Combustion Holes | 12 | 19 | 0 |
| Diameter of Secondary Combustion Holes | 3/8" | 3/8" | N/A |
| # of Airjets | 2 | 2 | 1 |
| Diameter of Airjets | 1" (cut at 45° angle) | 1" (cut at 45° angle) | 1.5" (cut at 90º angle) |
| Distance of Ashpan from Outer Hopper | 1.125" | 1.125" | |
| Overall Height of the Stove | 15" | 15.375" | 18.5" |

[1] Measured from inner cylinder.

## PROCEDURES:

1. Place three stoves in an area sheltered from the wind at the CPURE lab.
2. Weigh fuel sack for each stove.
3. Load rice hull stoves with fuel and prepare for startup (each stove has its own sack of fuel).
4. Place an ash pan under each stove to catch overflow fuel. Deposit overflow fuel back into hoppers before starting.
5. Place ash pan directly below stoves to catch all ash during operation.
6. Fill and weigh three pots with approximately 1 liter of water.
7. Note the water temperature and atmosphere conditions (temperature, humidity and average wind speed).
8. Prepare stopwatch for each stove. Burn time should be noted for each stove, approximately 20 minutes.

9. Light one stove at a time (drop lit piece of paper into combustion area) and note time start time for each stove.
10. Take thermocouple readings of flame temperature below each pot every two minutes.
11. Usability observations to be taken are:
    a. Start-up time
    b. Number of fuel bed fires
    c. Number of smoke events
    d. Number of "taps" required to maintain desired cooking temperature
    e. Boiling time for one liter in an uncovered pot
12. As burn proceeds, collect ash/char from each stove and save in a container to be measured when burn is finished.
13. After approximately 20 minutes, finish the burn by letting the remaining rice hull in the hopper burn out. Note time each stove finishes.
14. Weigh each fuel sack and note the weight of fuel used by each stove.
15. Measure the weight of ash/char for each stove.
16. Let the water cool to 50° C and measuring the final water weight.

## OBSERVATIONS

Observations were divided into two focus areas 1) usability data (Table 2) and 2) performance data (Table 3).

Candace Stryker made visual observations of usability characteristics. Recorded times included: the start-up time (time from when paper dropped into frustrum to time pot was placed on the stove); the water boiling time (from time of start-up); and the burn time (from start-up to the time the fire died). During the burn, the number of fuel bed fires and the number of smoke events were recorded. Major fuel bed fires were indicated if flame was present in the hopper, whereas minor fuel bed fires were indicated if the fuel in the hopper turned black and started to smoke. Smoke events were indicated if *combustion in the frustrum* produced smoke. Often, smoke events occurred after fuel delivery. "Fuel Delivery Required" was indicated every time the stove was tapped or lever moved. It should be noted that the lever on stove model 3 is a good fuel delivery device but tapping was still required in order to maintain an even fuel bed.

***Table 2: Usability Data for Trial 1, 2 & 3***

| Stove Model | Start-up time (pot on stove) (seconds) | | | Major fuel bed fires | | | Minor fuel bed fires | | | smoke events | | | Fuel Delivery required | | | Time to Boiling (mm:ss) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Trial | | | Trial | | | Trial | | | Trial | | | Trial | | | Trial | | |
| | *1* | *2* | *3* | *1* | *2* | *3* | *1* | *2* | *3* | *1* | *2* | *3* | *1* | *2* | *3* | *1* | *2* | *3* |
| 1 | 26 | 24 | 33 | 1 | 0 | 1 | 2 | 1 | 1 | 3 | 2 | 6 | 11 | 9 | 11 | 08:19 | 08:03 | 08:26 |
| 2 | 31 | 29 | 29 | 0 | 3 | 5 | 2 | 3 | 1 | 4 | 3 | 5 | 11 | 6 | 11 | 06:22 | 07:02 | 07:06 |
| 3 | 29 | 47 | 40 | 3 | 4 | 6 | 6 | 5 | 4 | 6 | 4 | 10 | 13 | 11 | 22 | 08:44 | 11:24 | 06:35 |

The performance data was collected by Serge Jizmundo and Ding Renacido using a bimetallic thermocouple and digital display. It should be noted that the batteries for the digital display died half way through trial 3. It was replaced with a simple mechanical thermometer.

Performance data is presented in Table 3 and includes: the burn time; original weight of water; weight of water vaporized; initial and final water temperature; weight of fuel used; weight of ash/char produced; and flame temperature readings.

*Table 3: Performance Data for Trials 1, 2, & 3.*

| Stove Model | Start time (hh:mm:ss) | Original water weight (kg) | Water Vaporized (kg) | Initial Water Temp (deg C) | Final Water Temp (deg C) | Fuel Used (kg) | Ash/char weight (kg) | Cooking Temperature (degrees C) | End Time (hh:mm:ss) |
|---|---|---|---|---|---|---|---|---|---|
| ***Trial One*** | | | | | | | | | |
| 1 | 11:51:15 | 0.975 | 0.420 | 32 | 96 | 0.615 | 0.155 | 330/291/240/305/261/239/267/284/257/290/174 | 12:15:51 |
| 2 | 11:52:07 | 0.970 | 0.405 | 32 | 96 | 0.615 | 0.175 | 305/353/311/276/268/260/244/307/302/303/256/150 | |
| 3 | 11:52:58 | 0.980 | 0.405 | 32 | 96 | 0.555 | 0.140 | 310/300/263/329/254/275/335/290/300/208/130 | |
| ***Trial Two*** | | | | | | | | | |
| 1 | 1:10:10 | 0.970 | 0.300 | 31.5 | 96 | 0.455 | 0.140 | 299/302/369/381/385/387/400/379 | 1:29:23 |
| 2 | 1:10:59 | 0.965 | 0.300 | 31.5 | 96 | 0.480 | 0.150 | 348/357/365/383/383/378/401/305 | |
| 3 | 1:11:45 | 0.980 | 0.240 | 31.5 | 96 | 0.350 | 0.105 | 300/328/339/362/385/304/326/306 | |
| ***Trial Three*** | | | | | | | | | |
| 1 | 1:56:27 | 0.970 | 0.500 | 33 | 96 | 0.670 | 0.195 | 204/371/401/361/392/379/322/371/372/332/450/450/346 | 2:25:56 |
| 2 | 1:57:21 | 0.975 | 0.490 | 33 | 96 | 0.725 | 0.225 | 206/460/446/385/397/400/355/364/330/300/448/300 | |
| 3 | 1:58:10 | 0.965 | 0.475 | 33 | 96 | 0.610 | 0.190 | 206/409/347/381/361/338/332/314/360/300/322/190 | |

The performance data is required to calculate the average flame temperature, fuel consumption rate (FCR), % ash/char produced and the overall efficiency. A digital scale was used to weigh the fuel used, water vaporized and ash/char produced.

## CALCULATIONS:

1. Fuel Consumption Rate (FCR)

   FCR = (weight of fuel consumed, kg) / (Operating time, min)

2. Percentage Ash/Char Produced

   %A/C = (weight ash/char, kg) / (weight of fuel consumed, kg) * 100%

3. Overall Efficiency

   Eff = (energy delivered to pot, kJ) / (energy available in fuel, kJ)

   = [(m*Cp*dT) + (Ww*Hfg)] / (Wf*LHV)

   Where:

   | | | |
   |---|---|---|
   | m | = | original mass of water, kg |
   | Cp | = | specific heat of water at 30° C, 4.225 kJ/kg/K |
   | dT | = | change in water temperature, kalvin |
   | Ww | = | weight of water evaporated, kg |
   | Hfg | = | heat of vaporization for water, 2.256 MJ/kg |
   | Wf | = | weight of fuel, kg |
   | LHV | = | Lower Heating Value of rice hull, 12.55 MJ/kg |

## ANALYSIS AND DISCUSSION

### *USABILITY*

Other than cost, one of the most important factors of successful technology transition is convenience. A new technology maybe better for the environment but if it is less convenient to use it will be difficult to sell in the communities. In general, with only a small amount of practice rice hull stoves (RHS) are comparable to wood stoves in terms of their convenience. Unfortunately the same cannot be said for LPG. LPG is extremely easy to use, produces few harmful emissions, and has an excellent temperature control mechanism. However, RHS's have two important advantages over LPG, these are operating cost and GHG emissions. In the Philippines, a family of five will spend ₱300-400/month on LPG while rice hull is free (with only a small cost for transportation of ₱3-20/month). The economic benefits of rice hull over LPG are tremendous and make RHSs a very important poverty alleviation tool. The other advantage of a RHS is the GHG emission reductions. LPG is a fossil fuel and all the $CO_2$ released from combustion is considered an anthropogenic contribution to climate change. Rice hull, on the other hand, is a crop residue that is considered a renewable fuel, and therefore the $CO_2$ from its combustion is not considered an anthropogenic contribution to climate change.

Given the need for a convenient cooking stove, it is important to distinguish the usability or convenience of each RHS. The usability results are averaged for all three trials and presented in Table 4.

***Table 4: Summary of Usability Results.***

| Stove Model | Start-up Time (seconds) | Major fuel bed fires | Minor fuel bed fires | smoke events | Fuel Delivery required |
|---|---|---|---|---|---|
| 1 | 28 | 0.7 | 1.3 | 3.7 | 10.3 |
| 2 | 30 | 2.7 | 2.0 | 4.0 | 9.3 |
| 3 | 39 | 4.3 | 5.0 | 6.7 | 15.3 |

The results presented in table 4 suggest that stove model 1 had the fewest fuel bed fires (both major and minor) and the fewest smoke events. The low number of fuel bed fires in models 1&2 is largely due to the heat shield. The shield acts as a fin, conducting heat away from the main drum to the atmosphere. It also insulates the fuel bed from heat given off by the main drum. Unfortunately, this is accomplished at the expense of heat delivered to the pot.

Model 1 had fewer fuelbed fires than model 2 which also has a heat shield. This is most likely due to model 1's larger hopper. Because the fuel in the hopper covers a larger area its thermal capacity is larger and will consequently heat up slower and result in fewer fuel bed fires. The large number of fuel bed fires in Model 3 is mostly due to the direct contact of rice hull with the main drum.

Model 1 also had fewer smoke events than model 2 and far fewer than model 3. Smoke events are the result of incomplete combustion. Because model 1 has a 7" frustrum (versus a 6 ¼" frustrum in model 2 and 5 ¼" frustrum in model 3) the air/fuel residence time in the combustion chamber is longer. A longer residence time increases the opportunity for fuel particles to combine with air and allow their combustion reactions to proceed all the way to $CO_2$. Turbulence from the twin jets in model 1 and 2 also promotes fuel/air mixing and complete combustion.

Model 2 required the least amount of attention for fuel delivery. This is expected because gravity can take advantage of the steep (60º) hopper angle, allowing rice hull to fall into the combustion chamber easily.

These results suggest that stove model 1 is the easiest to use and produces fewest problems.

## *PERFORMANCE*

The more scientific means of determining a RHS's usefulness is to analyze its performance characteristics; that is, how effectively can the stove transform the energy stored in rice hull into useful heat for cooking.

Performance results for the RHS's tested for trials one, two and three are presented in Table 5.

***Table 5: Performance Results for Trials 1, 2 & 3.***

| Stove Model | Total Burn Time (mm:ss) | | | Delta Temp (deg C) | | | Avg Flame Temp (deg C) | | | FCR (g/min) | | | % Ash/Char | | | Overall Efficiency (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Trial | | | Trial | | | Trial | | | Trial | | | Trial | | | Trial | | |
| | *1* | *2* | *3* | *1* | *2* | *3* | *1* | *2* | *3* | *1* | *2* | *3* | *1* | *2* | *3* | *1* | *2* | *3* |
| 1 | 24:36 | 19:13 | 29:29 | 64 | 64.5 | 63 | 276 | 363 | 366 | 25.0 | 23.7 | 22.7 | 25.2 | 30.8 | 29.1 | 15.7 | 16.5 | 16.5 |
| 2 | 23:44 | 18:24 | 28:35 | 64 | 64.5 | 63 | 290 | 365 | 366 | 25.9 | 26.1 | 25.4 | 28.5 | 31.3 | 31.0 | 15.2 | 15.6 | 15.0 |
| 3 | 22:53 | 17:38 | 27:46 | 64 | 64.5 | 63 | 286 | 331 | 322 | 24.3 | 19.9 | 22.0 | 25.2 | 30.0 | 31.1 | 16.9 | 18.4 | 17.4 |

From the summary results presented in Table 6, model 2 produces the highest average flame temperature which consequently resulted in the quickest boiling time. The higher flame temperature in model 2 is due to the larger quantity of rice hull fuel available in the primary combustion chamber; that is, there is more energy available to produce heat.

This conclusion is supported by the fact that Model 2 also has the highest fuel consumption rate (FCR). Model 2's 60º hopper delivers fuel at a faster rate than either model 1 or 3, which consequently produces a hotter flame but results in a lower overall efficiency and higher ash/char production. Because of its steep hopper, the residence time of the fuel in the combustion chamber is shorter, thus preventing all of the carbon fuel from escaping. Consequently model 2 is not able to release (by pyrolsis) all the energy stored in the rice hull and produces more charcoal (i.e. unburned carbon).

***Table 6: Summary of Performance Results for Trials 1, 2, & 3.***

| Stove Model | Average Burn Time (mm:ss) | Average Time to Boil (mm:ss) | Average Delta Temp (deg C) | Average Flame Temperature (degree C) | Average FCR (g/min) | Average % Ash/Char | Average Overall Efficiency |
|---|---|---|---|---|---|---|---|
| 1 | 0:24:26 | 0:08:16 | 63.8 | 334.9 | 23.8 | 28.4% | 16.2% |
| 2 | 0:23:34 | 0:06:50 | 63.8 | 340.1 | 25.8 | 30.2% | 15.3% |
| 3 | 0:22:46 | 0:08:54 | 63.8 | 313.1 | 22.0 | 28.8% | 17.6% |

Model 3 has the highest overall efficiency (17.3%). The higher efficiency in model 3 is probably due to a well designed fuel bed, lack of heat shield and close proximity of pot to flame. Because, the natural inclination of rice hull due to friction is also 45º the fuel bed directly below the combustion area has a uniform thickness and therefore uniform pyrolsis can be accomplished. Models 1 and 2 have an uneven fuel bed thickness (due to steeper fuel hoppers) thus making uniform pyrolsis more difficult. The small diameter of model 3's hopper limits the volume of rice hull and ash that is delivered to the ash pan, which results in a higher concentration of heat to the fuel in fuel bed and consequently more effective pyrolsis. Because model 3 does not have a heat shield it does not suffer the same heat losses as models 1 & 2 (unfortunately it suffers from excessive fuel bed fires).

Model 3's low fuel consumption rate produces a higher overall efficiency but it also results in a lower flame temperature. This low flame temperature produces a boiling time of 8 min 54 seconds, more than 2 min slower than stove model 2. Given the importance of convenience this will be a significant barrier to model 3's successful market introduction.

## CONCLUSIONS

With more than 1.5 million tonnes of recoverable rice hulls in the Philippines, which could subsequently be used as cooking fuel by more than 1 million families, the potential for rice hull stoves as a low-cost alternative to traditional cooking methods is immense. Large scale introduction of rice hull stoves could play an important role in the Philippines gradual shift away from fossil fuel and unsustainable firewood fuel to sustainable fuel sources.

The results of this experiment suggest that stove model 1 is the most convenient to use. It has the fewest fuel bed fires and smoke events while producing a relatively high flame temperature and short boiling time. The overall efficiency of model 1 is a respectable 16.2% while the fuel consumption rate is only 23.8 g/min. Although the overall efficiency is 1.4% less than stove model 3, the combination of high flame temperature and convenience make it the most likely candidate to be successfully introduced to the cook stove market.

The high efficiency of Model 3 is achieved by sacrificing convenience. The small diameter of model 3's hopper helps pyrolsis but it also limits the volume of rice hull and ash delivered to the ash pan; resulting in the need for more level action and tapping. Also, because model 3 doesn't have a heat shield it doesn't suffer the same heat loses as models 1 & 2 but this comes at the expense of more major and minor fuel bed fires.

Given that rice hull is largely a free fuel; small differences in efficiency will not appreciably affect consumers' preference in stoves. From user surveys, the initial purchase price appears to be the biggest barrier to acceptance of the stove. Reducing smokiness and stove supervision while increasing flame temperature are desirable attributes of a good stove that will strongly influence consumers willingness to buy and use a stove.