Analysis of Energy Flows in a Two-Stove Cooking System

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1. Introduction

The rating of stove performance almost always requires reporting the fuel efficiency – the efficiency with which fuel is applied to cooking tasks. If less fuel is needed from the available supply in order to accomplish a certain cooking task, the system is considered ‘more fuel efficient’.

The development of stoves which produce large quantities of charcoal requires stove testers to reconsider the fundamental basis on which evaluations have been made. Until recently, ‘fuel consumption’ was treated as pretty much the same thing as ‘heat transfer efficiency’ on the assumption that all fuel entering the stove is turned into heat and ‘transferred’ at some efficiency to a cooking vessel. These ‘char making’ stoves take fuel from the forest and turn it into charcoal while cooking. Each time they are used, they are loaded with a new charge of raw fuel from the forest. Each time they finish cooking, they have a significant mass of charcoal remaining which could serve as fuel for another stove or be applied as a soil amendment. If it is used in a second charcoal burning stove, the pair could be analysed as a single ‘cooking system’.

How the remnant charcoal is treated mathematically when reporting the fuel efficiency is critical to the assessment of a two-stove cooking system. The following analysis demonstrates how this might be calculated, for the individual stoves and as a pair.

2. The Two Stove Cooking System, wood stove Stove1 and charcoal Stove2

Consider two stoves used together: a wood stove that cooks and creates charcoal as a by-product and a charcoal Stove2 that cooks using most of the char produced by Stove1.

2.1. Mode of operation, Stove1

Raw fuel is harvested from a forest and the net energy content is 10 Megajoules (MJ). The fuel is placed into Stove1 and ignited. Some of the fuel is transformed into heat and there is a mass of remnant charcoal that contains 5 MJ of available energy (half the original amount). The heat is transferred to a pot at an efficiency of 50%. Thus 25% of the original total energy available, 2.5 MJ, is delivered into the pot. In this example, gases are assumed to have burned perfectly so there is no loss of chemical energy.

2.2. Fuel Remaining

The remnant fuel is charcoal and varies in size from recoverable large chunks to powder in the ash. The carbonaceous ash is discarded. Very small char chips are also discarded. In this example, the lost fuel mass contains 10% of the original energy of the original fuel placed in Stove1, or 1 MJ. Some char is large enough to be ‘fuel’ for Stove2. The usable fuel mass placed into Stove 2 contains 40% of the original energy: 4.0 MJ.

2.3. Mode of operation, Stove 2

The recovered charcoal with an available energy content of 4.0 MJ is placed in Stove 2 and ignited. It burns to completion transferring some of the heat – 1.6 MJ – into a second pot. After the burn is completed some carbon remains in the ash with an energy content of 0.5 MJ. There is no recoverable fuel. Of the available 4.0 MJ, 1.6 was delivered into the pot, 0.5 MJ was lost in the ash and 1.9 was lost as hot gases (assuming perfect combustion).

2.4. Energy Trail:

Stove1
10 MJ available in the fuel taken from the forest
2.5 MJ transferred to the pot
2.5 MJ lost as hot gases past the pot
4 MJ recovered in the form of charcoal from Stove1
1 MJ not recovered, in the ash

Stove2
4 MJ available in the fuel recovered from Stove1
1.6 MJ transferred to the pot
1.9 MJ lost as hot gases past the pot
0.5 MJ not recovered, in the ash

2.5. Energy Efficiency

An efficiency is a ratio. The energy efficiency is the ratio of the energy that gets into the pot divided by the energy available from the fuel needed to conduct (or replicate) the experiment. The "fuel efficiency" is the *energy* delivered to the pot divided by the *energy* in the mass of new fuel needed per replication. It can also be called the Energy Efficiency.

Pot Energy per cycle/Fuel energy per cycle = Energy efficiency

The energy efficiency of Stove1 is calculated by dividing the energy gained by the pot (2.5 MJ) by energy in the fuel placed into the stove (10 MJ).

Stove1 Energy Efficiency = 2.5/10 * 100% = 25%

Some heat bypassed the pot, some remained in uncombusted fuel. Not all the remaining fuel was recovered for Stove 2 because it was impractical.

The energy efficiency of Stove 2 is calculated by dividing the energy gained by the pot (1.6 MJ) by energy in the fuel placed into the stove (4.0 MJ).

Stove1 Energy Efficiency = 1.6/4.0 * 100% = 40%

Caution The overall efficiency of the two stoves working together is ***not*** 25% + 40% = 65%. Those ratios based on different pairs of numbers. It is not true that 65% of the original energy available was transferred the pots. It was much less than that.

The energy efficiency of the cooking system – the pair of stoves – is calculated by adding the heat gained by both pots (2.5 + 1.6 MJ) then dividing by the total heat available from the fuel (10 MJ).

Energy efficiency of Stove1 = 2.5/10 * 100% = 25% using only part of the energy available
Energy efficiency of Stove2 = 1.6/4.0 * 100% = 40% using most of what energy was left
Energy efficiency of the 2-Stove system = (2.5 + 1.6) / 10 * 100% = 41% overall

The total energy lost in unrecoverable char is (1.0 + 0.5). Of the original total 10 MJ, 4.1 MJ was delivered into the two pots, 0.15 MJ was lost in the small charcoal pieces and carbonaceous ash while the remaining 4.4 MJ was lost as hot gases.

2.6. Thermal Efficiency

The thermal efficiency is the fraction of energy that was theoretically released by the fire, considering only the fuel actually combusted. In this example the combustion efficiency is assumed to be perfect. The energy released (10-5.0) is a smaller number than energy in the total mass of fuel placed into Stove 1 because only half of the available energy was freed by the fire. Energy in the pot (2.5) divided by the energy available from combusted fuel (5.0).

Thermal efficiency of Stove 1 = 2.5 / 5.0 * 100% = 50%

The thermal efficiency is much higher than the energy efficiency because the denominator is the heat released by the fire, not the fuel energy *available* to the fire. The same calculation is done for Stove2 using the pot energy (1.6) and the heat released (4.0-0.5).

Thermal efficiency of Stove 2 = 1.6 / 3.5 * 100% = 45.7%

The thermal efficiency of the two stoves working together is ***not*** 50% + 45.7% = 95.7% because the ratios are based on different pairs of numbers. Further, 95.7% of the energy did not end up in the pots so it cannot be correct.

The thermal efficiency of the two-stove cooking system is calculated by adding the heat gained by both pots (2.5 + 1.6 MJ) by the total heat released from the fuel (5.0 + 3.5 MJ). Of the original 10 MJ total energy available, 4.1 MJ was delivered into the two pots, 1.5 MJ was lost in the small charcoal pieces and carbonaceous ash and the remaining 4.4 MJ was lost as hot gases.

Thermal efficiency of the 2-Stove system = (2.5 + 1.6) / (5.0 + 3.5) * 100% = 48.2%

3. Selecting the Reporting Metric

The reporting metrics must match the needs and expectations of the user of the information.

3.1. The stoves can be calculated separately or as a pair, therefore they can also be reported separately or as a stove system.

Stove 1:

Energy Efficiency	25.0%	because there was a lot of char remaining (unburned fuel)
Thermal Efficiency	50.0%	because half of the heat released was delivered to the pot

Stove 2

Energy Efficiency	40.0%	some charcoal remained but heat transfer efficiency is high
Thermal Efficiency	45.7%	because half of the heat released was delivered to the pot

Stove 1 + Stove 2

Energy Efficiency	41.0%	All energy gained by all energy available from the raw fuel
Thermal Efficiency	48.2%	All energy gained by all energy available from the fire

The energy lost in the unburned, unrecoverable char is a ‘mechanical loss’. If there was less than perfect combustion, the formulae above would also have to consider the ‘chemical losses’ of partly burned emissions such as CO and H_2.

3.2. If asked for a number representing the fuel consumption of Stove 1, it is 25%, the Energy Efficiency. The calculation of Thermal Efficiency calculation does not consider the mass of fuel consumed per task so it cannot represent it.

3.3. An open fire with an energy efficiency of 10% would use two and a half times as much fuel as Stove1. 25%/10% = 2.5. A comparison of the energy efficiencies of two stoves gives their relative fuel consumptions.

3.4. Conclusions

3.4.1. The Energy Efficiency Stove2 is more energy efficient that Stove1 because it combusts almost all the fuel available. Stove1 is better at transferring what heat it liberates from the fuel but leaves a lot of it unburned. Stove2 has a lower Thermal Efficiency because less than half the heat liberated is transferred to the pot.

3.4.2. Analysed as a single system, the individual energy and thermal efficiencies can be reported. The Energy Efficiency of each stove can be compared with other stoves. The pair can also be compared with another single stove or pairs of stoves.

3.4.3. While the two thermal efficiency numbers could be combined, the result contains no useful information. The two ratios involve 4 difference values so the combined Thermal Efficiency has no meaning to a designer or user. It would be like combining the colours of a blue car and a yellow car. You would get ‘green’ but it doesn’t tell you anything useful about either car. It is the combined Energy Efficiency that contains useful information because it relates to the fuel consumed and the work done.