EMISSIONS REDUCTIONS FROM DOMESTIC COAL BURNING: PRACTICAL APPLICATION OF COMBUSTION PRINCIPLES

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ABSTRACT

We present a discussion of the combustion processes taking place in a household 'mbaula', using both the conventional and top-down fire lighting methods. After explaining why it reduces emissions, we then present in concept the conditions required to achieve significant emissions reductions (trace gases and particles) in a domestic coal-burning appliance, taking into account primary and secondary air flows, coal and coke burning stages and heat transfer processes. Results are presented of emissions measurements from a novel domestic heating stove designed on the basis of these principles, and constructed using affordable materials and appropriate technologies. These results suggest that significant improvements in domestic energy use, efficiency, and air quality are possible for the poorer communities of the South African interior, while burning untreated Witbank Grade D coal.

1. INTRODUCTION

Combustion of coal remains the prevalent energy source for space heating and winter cooking in the townships and informal settlements of the South African Highveld. Inefficient combustion of the coal results in high emission rates of particulate matter comprised mostly of condensed droplets of semi-volatile hydrocarbons, carbon monoxide and sulphur-containing gases (hydrogen sulphide and sulphur dioxide). The top-down fire lighting method (also known colloquially as the *Basa Njenga Magogo* method) results in a significant (up to 80%) reduction in particulate emissions, which becomes immediately evident when the far greater smoke production of a bottom lit, upward burning (conventional) mbaula is compared with the much lower volume of smoke produced by a top-lit downward burning mbaula (coal brazier constructed out of a twenty litre steel drum). Despite extensive promotion by the Department of Minerals and Energy of the *Basa Njenga Magogo* method by means of mass implementation campaigns, very little research has been carried out to understand the scientific basis for why the method works, or how it could be optimised by rational design principles to produce more efficient and cleaner burning stoves.

2. RATING COMBUSTION CLEANLINESS

In the past many stove developers have convinced themselves that their stoves are burning 'cleaner' than previously - whatever the device they have been working on - because they have not completely understood what the instruments used to measure stove emissions are telling them. For example, the quantity of air diluting a gas sample can vary widely. Therefore, it is necessary to factor out all the oxygen in the calculation of emission factors (EF), to derive factors are independent of the exigencies of dilution and representative of the combustion process itself. Correctly calculated, the resulting emission factors are a measure of combustion performance that enables meaningful comparisons to be made across different stoves and fuels.

To get an EF it is necessary to measure at least two gases: carbon monoxide (CO) and oxygen (O_2). The CO level in parts per million (ppm) factored for the O_2 and CO_2 present in the sample gives an *Excess Air* (EA) corrected *Emission Factor* for the CO (CO_{EF}). CO_2 can be calculated reasonably (but not exactly) from the O_2 level.

In its simplest form, *Excess Air* (EA) is calculated thus:

$$EA\% = [O_2 + ½CO] / (209{,}005 - [O_2 + ½CO]) * 100\%$$

Lambda = λ = EA + 100%; and
$CO_{(EF)} = \lambda \times CO_{ppm(v)}$

For indoor flame-based devices (such as paraffin stoves) $CO_{(EF)}$ should be less than 3 800 ppm (corresponding to a ratio $CO:CO_2 \leq 2\%$ in terms of SABS standards).

This calculation can be done with **%** or **ppm** as long as the mode is consistent. *20.95%* (209,500 ppm) is the background concentration of oxygen in the atmosphere, and $\mathbf{O_2}$ is the oxygen level measured in the gas sample.

Example 1
Ambient O_2 = 20.95% = 209 500 ppm
Measured O_2 = 20.0% = 200 000 ppm
Measured CO = 1 500 ppm
EA = 1944% = factor of 19.44
λ = 2044% = factor of 20.44
$CO_{(EF)}$ = 1 500 x 20.44 = 30,659 ppm

Example 2
Ambient O_2 = 20.95% = 209 500 ppm
Measured O_2 = 11.3% = 113 000 ppm
Measured CO = 2 985 ppm
EA = 114% = factor of 1.14
λ = 214% = factor of 2.14
$CO_{(EF)}$ = 2 985 x 2.14 = 6,382 ppm.

λ can also be used to calculate an Emission Factor for other gases and particulates in samples measured at the same time. The dilution of the sample by transient air makes no difference to the resulting EF provided (a.) the dilution factor is relatively steady and (b.) the instruments have approximately the same response time. If these preconditions are met, emission test results will be comparable.

3. COMMONLY USED COAL BURNING TECHNOLOGIES

Mbaula[*] is the African name of a well known basic heating and cooking technology that consists of a 20 litre bucket with holes in it. The Mbaula is not quite as simple as one might imagine. The bottom of the bucket is criss-crossed with wires to create a grate that lets air under the coal across the entire bottom of the fire (Figure 1). With this wire in place the rate of burning is increased allowing a person to cook quickly and also to use less total coal.

Figure 1: Wire grate in an mbaula

The conventional use of the mbaula is as follows. Coal is laid on top and it is 'middle lit'. This means the wood is placed on some of the coal, lit and the rest of the coal thrown on top. A second bottomless tin is placed over the top to increase the draft and accelerate the ignition. The ends of wire grate supports are visible at the reddish burn line in Figure 2. The coal in this picture was ready for cooking after 45 minutes.

Figure 2: Mbaula with temporary drafting stack

The volatiles are boiled and/or burned off and the result is a hot bed of burning coke. This process is the major cause of visible smoke pollution in the townships. During this process the $CO_{(EF)}$ rises to 50,000 ppm and beyond.

The well known result of this method is that coal is roasted with no flames (Figure 3a) to drive off the smoke until flames breach the top layer (Figure 3b).

Figure 3: Conventional mbaula: (a) Just starting to light emitting semi volatile organic smoke; (b) Well lit coal after ~30 minutes

Heat released when coking is usually wasted. Something like 25-40 % of the fuel is consumed before cooking starts. In addition, in this condition, as much as two thirds of all sulphur is emitted as H_2S, rather than as SO_2 as is commonly supposed.[†] When secondary combustion of the coal gases is established, a flame is sustained.

Analysis of the combustion: The red-hot coke provides a continuous ignition source for the gases which are heated

[*] Adapted from the word 'barrel', also variously spelled *mbawula, embaula, embawula, imbawla*. Several new commercial products bearing no resemblance to it also use or have registered the word as their product name.

[†] SeTAR Centre emission tests of a conventional mbaula, unpublished.

as they pass up through the hot coke bed. Once this condition is established, the mbaula tends to make little visible smoke, though it is by no means clean burning. High levels of carbon monoxide (CO) are produced. Significant quantities of hydrogen (H_2) and H_2S have been measured in the early stages of a burn, with unexpectedly high levels of H_2 and CO in the late stages. A graph of combustion efficiency for a typical mbaula burn is shown in Figure 4. An $H_{2(EF)}$ level of 12,000 ppm is not unusual and $CO_{(EF)}$ can reach into the hundreds of thousands of parts per million. A CO/CO_2 ratio of 150% is not unknown. The legal limit in most countries for flame-based cooking stoves and fuels is 2% (for indoor combustion devices). A lot of attention has been paid to visible and PM10 particulates but little to CO and fine particulates (less than 2.5 μm diameter).

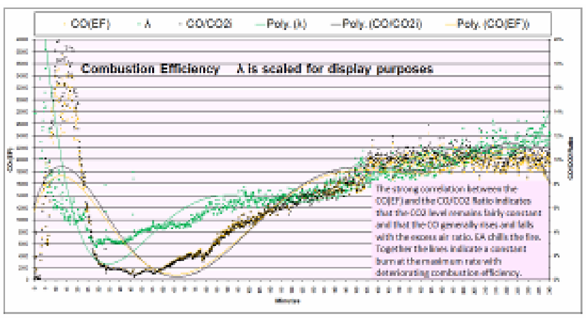

Figure 4: Combustion efficiency of an mbaula lit in a standard fashion

Combustion in most conventional cast iron domestic coal stoves is similar to the mbaula. These devices were designed in the 1800's. They typically last a long time. Owning one is widely seen as a positive statement about the household's income level. There is an extensive and diversified inventory of the cast iron stoves in urban townships that produce large volumes of smoke,

There are several major technical problems with these conventional cast iron stoves:

- Over the past 100 years there has been little advance in the designs of cast iron stoves.
- The minimum load that will burn properly is still in the 6-10 kg range, with major smoke emissions early in the burn as the coal is coked.
- They are expensive.
- The chimneys are usually too large in diameter and too short to work properly.

4. TOP LIT UP-DRAFT (TLUD) STOVES

This is the correct name for the combustion method known colloquially as *Basa Njenga Magogo* (make fire like Granny does). It uses the same mbaula drum with grid, but with the fire lit at the top, with only a few coals placed above the wood. The fire slowly burns downward as the top layer of coal becomes coked (pyrolysed) first, turns red hot, and thereafter ignites the mix of gases emerging from the coal lower down in the stove. There is a considerable reduction of visible smoke but no other major change in the basic operation of the coal stove or mbaula. The period of time during which $CO_{(EF)}$ is high (20,000 to 60,000 ppm) is shorter because a hot coke bed is established sooner.

Because the *Basa Njenga Magogo* (BSM) method reduces the visible portion of the emissions, it is generally assumed that the fire is burning much cleaner throughout the entire combustion cycle. We have discovered that once the coal is coked, there is no difference at all in emissions. For most of the remainder of the burn, emissions are the same, save for the possibility that the top coals which ignite first will burn to ash before the coal at lower levels in the stove. The formation of a top layer of ash above the hot burning coked coal at the end of a burn in the BNM appears to cause the CO output to increase (relative to the conventional bottom up method of lighting a coal stove). This increase in CO takes place because the BNM stove lacks a CO top flame for a longer period at the end of the burn. Bare coke plus sufficient air flow is required to maintain a flame. Without the hot coke to sustain a CO burning flame, the device emits CO in large quantities, posing an immediate danger to anyone who takes an mbaula indoors for space heating or even persons who stand near it while in operation outdoors [1][‡].

The major problems associated with the mbaula, top-lit or bottom-lit, include:

- though heat transfer efficiency from burning coke is in the 40% range[§], the mbaula manages to deliver only a tiny fraction of the heat energy in the coal to the pot – below 5% - because of its overall low efficiency
- a large initial fuel load needed
- time taken to ignite is excessive
- it is difficult to extinguish and when it has been extinguished, the coke is difficult to re-ignite later
- adding fuel creates a large pulse of new smoke
- there is no meaningful control over the heat output
- the mbaula has a short operational lifetime
- there are negative health consequences just from standing near it and breathing (CO and particles)
- it is dangerous/deadly to use it as a space heater in confined spaces.

5. ALTERNATIVES COAL BURNING TECHNOLOGIES - COAL GASIFIER STOVES

While it can be argued that all coal fires are gas fires, the term 'gasifier' refers to a stove designed to generate coal gas, cook with it and leave at least some coke at the end. It is possible to build a coke gasifier, however it is more common to think of a gasifier as a stove that creates and burns only the volatiles in a fuel.

A natural draft gasifier needs a chimney. A fan powered version has better heat control. At this time no commercially available coal burning device suited to township cooking is known to the authors.

The problems with gasifiers are:

[§] Tests conducted at SeTAR Centre, Dec 2008, unpublished

- more complex to operate; can produce noxious fumes when things go wrong
- are not yet well engineered for small scale applications; large ones are well known as they supply 'coal gas' in piped gas systems
- may produce large quantities of unwanted coke, forcing the cook to purchase more fuel
- it can be difficult to change the power level while yielding quality gas.

6. FEATURES OF A STOVE SUITABLE FOR LOW INCOME HOMES

Some of the features required for a high performance domestic coal stove that will be attractive to a large number of coal using households in the RSA would include:

- easy and fast lighting
- short time between lighting and starting to cook
- low emissions
- controllable heat output
- can serve as a cooking stove as well as a space heater
- can be fuelled with small, medium and large quantities of fuel
- can be refuelled without the need to re-light
- cooks two or more pots at the same time
- multi-fuel capability, at least wood and coal
- affordable by the target market
- long lasting, ready supply of replacement parts and easy to repair
- appealing to the eye
- safe to use in the home.

7. EXPERIMENTATION AND PROGRESS WITH DOWN DRAFT STOVES

Bottom-Lit, Down Drafting (BLDD) devices are promising candidates for meeting at least the basic demand of low emissions. In this section, examples of BLDD are presented to illustrate some of their most advantageous features (Figures 5 to 12).

Figure 5: Single pot BLDD stove

Figure 6: Single pot downdraft stove with air pre-heater and pot in place

The BLDD is able to maintain a flame projecting downward below the grate because the ash keeps falling away exposing burning coke. Tests run by the first author at New Dawn Engineering [2][**] in 2004 showed that the ash formed at the burning face of the grate of a BLDD coal stove does in fact naturally fall downward as the coke is combusted. In principle, the BLDD uses gravity and the draft to get rid of ash. In Figure 6 the coal is inside the stainless steel sleeve and the ash falls to the bottom right of the sloping pipe. The pot is heated by the top of the burning coal and the flame is underneath. It is very inefficient but better than an mbaula. It is basically smokeless.

If the grate is made from thin wire, not steel bars or cast iron, there is much less tendency for the ash to accumulate to the point of blocking air flow. Wire cannot support ash very well as the ash is cut by the wire, in this case 1.2 mm diameter.

The double tube (Figure 7) creates a fuel hopper in which the coal is pyrolysed in the centre, and has a secondary air pre-heating tube around it. The fuel is normally covered by a plate with a central air hole to ensure the incoming air stream is fast enough to prevent coal fumes escaping upwards back into the living space. Gases are drawn downward through the coke bed. This cracks any moisture through the water gas shift reaction [3] and yields high quality coal gas under the grate.

Figure 7: Partially pyrolysed coal in a double tube fuel hopper

Success with the single pot stove led to the development of a two pot version (Figures 8, 9 and 10). The efficiency remained low because of the high surface area. The lower stainless steel shield in Figure 8 is a preheater.

Figure 8: Two-pot down draft stove

Figure 9: Boiling both pots on the BLDD stove

Figure 10: Burned coke in the BLDD stove

Placing this down draft mechanism in a box produces a stove that can cook two pots at once. Figure 11 shows a stove that was field tested in eight homes in the Gauteng area. A 5 litre pot (only the lid is visible) is sunk into the stove body for heating water.

Figure 11: BLDD two pot stove with conventional appearance (New Dawn Engineering, 2004)

In 2007 a 15 kW BLDD burner was constructed in Ulaanbaatar, Mongolia, to serve as a reference burner, against which proposed improved lignite burning stoves could be compared (Figures 12 and 13). A feature of the device is the small size of the fire. The smaller the fire, the more difficult it is to burn cleanly. For reference, both Mongolian and Gauteng informal homes need about 3-4 kW for heating and cooking.

Figure 12: Mongolian Reference Burner (MRB)

Figure 13: MRB BLDD burner when hot

When lit and running hot the MRB (Mongolian Reference Burner) has a $CO_{(EF)} = 12$ ppm. To put this in perspective, burning lignite [4] in this \$20 device has a CO/CO_2 ratio as low as 0.006% during long portions of the burn. Presuming that the ash is occasionally removed and the coal is replenished from time to time, a $CO_{(EF)}$ of 500 can be expected from a commercial appliance that could be fabricated by a township-based metal worker.

Since late 2008, with the establishment of the Sustainable Energy Technology Testing and Research Centre (SeTAR Center) at the FADA Complex, University of Johannesburg, work has continued on stoves employing the downdraft principle. The first SeTAR BLDD prototype was an attempt to build a space heater. Components of the first device - a basic space heater, comprising a fuel chamber, combustion chamber, a 230 mm cube body and a 75 mm diameter chimney - are shown in

Figure 14. The grate is made from high temperature element wire which can operate at 1 300° C.

Figure 14: SeTAR Mk I BLDD coal stove in operation with 94 mm diameter burner

A 94 mm diameter fire

(Figure 15) proved unable to keep the chimney hot enough to provide the draft required. Careful observation discovered a major source of CO. The problem with too little draft (a chimney that is too large in diameter and too short) is that the coal pyrolyses upwards through the fuel bed and gives the appearance of burning well. Without enough draft, insufficient oxygen reaches the bottom of the fuel pile and the flame under the grate is gradually snuffed out. The $CO_{(EF)}$ rises rapidly past 20,000. It basically becomes a CO generator. The thermal efficiency, as measured between the ambient air and the temperature in the chimney, was over 90%, which is dangerously high. A target of 80% is realistic for a small stove.

Figure 15: Combustor parts of the SeTAR Mk I BLDD coal stove

Two solutions were tried. First the diameter of the fuel hopper in which the coke is produced was increased to 125 mm. This succeeded in creating enough heat to keep the chimney hot and to pull enough air downward through the fuel so there was always some O_2 at the grate (Figure 16).

This layout provided a 4 kW fire with consistently low $CO_{(EF)}$ in the 550-850 range. Considering the stove has such a small fire chamber and coal charge, this is a very clean burn. It has a CO/CO_2 ratio of about 0.7%, a 95% reduction in CO compared with an mbaula.

Figure 16: SeTAR Mk II BLDD coal stove with 125 mm diameter burner

Second, a small tube was placed under the grate to introduce secondary air where it was most needed (Figure 17).

Figure 17: 16 mm tube added under the grate

The addition of secondary air below the fire grate worked spectacularly well and corrected an earlier impression that the introduction of secondary air contributed to a rise in CO and caused the flame to extinguish. The key was to limit the amount of secondary air introduced below the fire grate to just enough to keep the flame alive and no more.

A new problem was that the small blue CO flame of a coke fire could be easily blown out by air entering at right angles. The instability of the CO flame is managed in one of two ways: either close the secondary air hole once the coal was coked (which was discovered to work well) or bring the secondary air into the combustion chamber tangentially so as to leave the centre of the flame undisturbed.

The orange flame, pictured through the 16 mm secondary air tube (Figure 18) is typical of the combustion of coal volatiles, in this case Witbank Grade D. It is noisy because the air rushing through the tube continuously blows the flame out and it re-ignites at a high frequency.

Figure 18: Combustion while pyrolysing in a SeTAR BLDD stove

The blue flame (Figure 19) is primarily CO burning. The dark patch on the left is caused by clean air blowing the flame aside. In this condition the weak flame extinguishes too easily. The CO/CO_2 ratio is about 0.7%.

Figure 19: Combustion after pyrolysis is done

Again by experimentation, it was discovered that adding a small vane to the inside end of the tube directs the air around the periphery of the combustion chamber. In response the flame burns quietly and it is stable throughout the burn without needing intervention by the stove user to open and close the secondary air inlet.

8. PROVISIONAL CONCLUSION FROM WORK IN PROGRESS

The SeTAR BLDD stove with a wire grate and tangential secondary air injection lights quickly and burns very much cleaner than an mbaula. It is cost efficient and can be made using simple welding shop tools typical of those found in any well equipped metal working shop .

The CO emission reduction is on the order of 95% compared with an mbaula. It is expected that the PM10 and PM 2.5 emissions will be similarly reduced, but the particulates produced by the BLDD stove prototype still have to be quantified.

A power level of up to 4 kW was successfully maintained during a trial run of several hours. Because of the down draft configuration, the SeTAR down draft stove can be refuelled without creating a new pulse of smoke or large transient pulse of CO. It can be lit with as little as 300 grammes of coal (two big handfuls). The prototype BLDD stoves were all fabricated out of scrap materials and have work very well. Once the basic design principles and fabrication techniques have been perfected, the SeTAR BLDD stove will become a knowledge package that can be transferred to many different types and scales of producers.

The basic concept of the BLDD stove can be easily modified for cooking multiple pots, heating an oven, warming water, space heating, and/or other specialized functions by changing the size and shape of the box.

9. FUTURE RESEARCH

This version of the BLDD stove can still be greatly improved. With a perfectly optimized stove the H_2 would drop to zero and the $CO_{(EF)}$ would fall to below 400. The challenge ahead is find out how to maintain these low emission rates while building even smaller fires. One aim of the developers of the BLDD SeTAR Stove is to figure out how to sustain low emissions while reducing the power output to 2.5 kW and bringing the coal consumption down to about 360 g per hour (of 25 MJ/kg coal).

[1] Air Quality Management and Climate Change: A Call for Local Action, H Annegarn, 6 June 2007, http://www.joburgair.org.za/Files/annegarnaqm_presentation.pdf

[2] New Dawn Engineering, Matsapha Swaziland www.newdawnengineering.com

[3] http://en.wikipedia.org/wiki/Water_gas_shift_reaction

[4] The lignite is mostly from the Nalaigh coal mine near Ulaanbaatar: 30% moisture, 20% ash, 25% volatiles. 25% carbon is a typical analysis. Sulphur is low.

END

Crispin Pemberton-Pigott has worked with Appropriate Technologies for 30+ years, largely designing labour-based manufacturing equipment. A stove maker for 25 years, he won the DISA Chairman's Award 2004 for the Vesto Stove made by his company, New Dawn Engineering. He is a co-founder of the Eastern Cape Appropriate Technology Unit, the Renewable Energy Association of Swaziland and the Industrial Designers Association of South Africa. Presently he advises two Mongolian clean air projects and is the senior technical advisor at the *Sustainable Energy Technology Testing And Research* (SeTAR) Centre at the University of Johannesburg. He volunteers at ETHOS and SABS co-writing stove standards and test protocols. For more information visit: www.newdawnengineering.com. crispin@newdawn.sz

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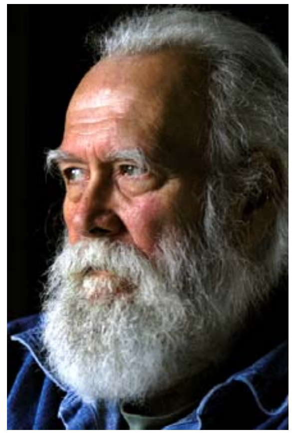

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