Calculating Energy Efficiency Using A Chemical Mass Balance Method

Crispin Pemberton-Pigott

Reporting research on the combustion of solid fuels conducted at

SeTAR Centre, University of Johannesburg
Cape Peninsula University of Technology, Cape Town
China Agricultural University, Beijing

Presented at

Brookhaven National Laboratory – 7 April 2016

Problem Statement

Test methods assume that the fuel burns and dries homogeneously

If this was true there would not be a "char-burning phase"

Emissions and efficiency are miscalculated because of this assumption

Energy Efficiency:

An efficiency is a ratio:

$$\frac{\text{Useful Energy Delivered}}{\text{Energy available in the fuel consumed}} \times 100\%$$

Consumed: Combusted to the point where remainder is abandoned

Energy Efficiency:

An efficiency is a ratio:

$$\frac{\text{Useful Energy Delivered}}{\text{Energy available in the fuel consumed}} \text{ X } 100\%$$

How is this determined?

Consumed: Combusted to the point where remainder is abandoned

Slide 4

H1 Harold, 2016-04-07

Fuel Analysis – MASHCON

M	Moisture
A	Ash
S	Sulphur
H	Hydrogen
C	Carbon
O	Oxygen
N	Nitrogen
HHV	Higher Heating Value

Fuel Analysis – MASHCON – Examples

Ultimate analysis (dry) in a mass basis

FUELS:	Albasia Charcoal	Albasia Pellets	Baganuur Coal	Baylag Erdene Coal	Lump Charcoal	Coffee Husks	Corn Cobs	Delmas Mine Coal
Ash %	2.25	0.75	7.18	26.47	6.66	2.50	3.02	20.00
Carbon %	82.00	49.40	74.10	61.64	79.00	49.32	46.35	63.00
Oxygen %	13.85	43.60	12.90	8.18	12.45	41.20	44.25	11.00
Hydrogen %	1.78	5.99	4.68	2.19	1.69	6.10	5.84	4.50
Sulphur %	0.02	0.01	0.19	0.52	0.10	0.07	0.09	1.00
Nitrogen %	0.10	0.25	0.95	0.99	0.10	0.81	0.45	0.50
Total %	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
HHV	29.47	19.85	16.00	23.73	29.80	18.34	17.65	18.19
LHV	29.05	18.45	14.91	23.22	29.41	16.92	16.29	17.14
DAF HHV	30.15	20.00	17.24	32.27	31.93	18.81	18.20	22.74
O/H Ratio (m)	7.78	7.28	2.76	3.73	7.37	6.75	7.58	2.44

Fuel Analysis – MASHCON – Multi-fuel

Determination of the fuel composition can be challenging

New Raw Fuel	Reusable fuel Net change	Unusable fuel Discarded	
Albasia Pellets	Reusable Albasia Pellets	Charcoal	
8.21	-	-	% WWB
0.69	0.75	6.66	Ash
0.01	0.01	0.10	Sulphur
5.50	5.95	1.69	Hydrogen
45.34	49.42	79.00	Carbon
40.02	43.62	12.45	Oxygen
0.23	0.25	0.10	Nitrogen
100.00	**100.00**	**100.00**	%
1,017	0	220	
		797	Total burned, g
		10.8	Total energy yielded, MJ
		1,017	Total consumed, g
		13.8	Total energy available, MJ
		2.98	Total energy wasted, MJ

Fuel Analysis – MASHCON

Determination of the fuel composition can get complicated **II**

As Burned Ash-Free heat content - ABAF

Fuel As Burned	Analysis as burned	
Moisture % of fuel As Burned (AB)	10.37	% WWB
Ash % As Burned	- 0.49	% Wet Basis
Sulphur % As Burned	0.01	% Wet Basis, Ash in
Hydrogen % As Burned	6.54	% Wet Basis, Ash in
Carbon % As Burned	35.70	% Wet Basis, Ash in
Oxygen % As Burned	47.61	% Wet Basis, Ash in
Nitrogen % As Burned	0.27	% Wet Basis, Ash in
Data check	**100.00**	% Wet Basis, Ash in
Heating Value (HHV) Dry, ash in, As Burned	17.12	MJ/kg Dry This value
Heating Value (LHV) Dry, ash in, As Burned	15.44	MJ/kg This value =
Heating value As Burned	**13.57**	MJ/kg This value is
ARV Factor conversions to mass/kg As Burned (AB)	**0.995**	Multiply emissions p
DAF Factor for conversions	**1.110**	Multiply emissions p
Raw Fuel Heat Value AR, considering moisture	**16.72**	MJ/kg Used to calcu
As Burned Ash-Free heat content - ABAF	**13.51**	MJ/kg This value is u
Dry Ash-Free - DAF	**15.06**	MJ/kg To be used fo

Collect the Products of Combustion

Tracking the combustion is challenging too

B.E.S.T. Lab, CAU College of Engineering

Heat Gained – Space Heating

Calculate what energy was available in the fuel

Calculate the losses up the stack

- Siegert Method – estimates losses up the stack
- Gas-by-gas calculation – estimate losses up the stack

Heat Gained, by subtraction

Step 1: Combust the Fuel

Remove the ash and convert to Molar Elements

Combustion			
This calculation is done with fuel, wet or not, and no excess air			
	Mass %	Moles	Gas names
Homogeneous combustion of fuel ARAF			
	Ultimate Analysis Ash Free, % Mass	Moles of elements in fuel/kg + water	Principle Emissions
Carbon	75.55	62.90	< Fuel C
Oxygen	13.15	8.22	< Fuel O
Hydrogen	4.77	47.34	< Fuel H
Moisture in Fuel	5.37	5.96	< H in fuel H_2O
Oxygen content of H2O		2.98	< O in fuel H_2O
Sulfur	0.194	0.06	< Fuel S
Nitrogen in Fuel	0.969	0.69	< Fuel N
Argon from Air			Air Ar >
N2 from air			Air N_2 >
Total	100 g	128.15	

Step 1: Combust the Fuel

Combust in Air

Burn in air, no EA Undiluted			
Undiluted moles of gases after burning	Added combustion air containing O_2, N_2, Ar and CO2	Total Moles of Combustion Gases	Total % of Wet Combustion Gases
62.90	0.1357	63.04	17.59
			-
23.67			-
2.98		26.65	7.44
0.06		0.06	0.02
0.69		0.69	0.19
	3.1675	3.1675	0.88
	264.80	264.80	73.88
90.3 moles of gas	268.1 moles gas+air	358.40	100 %

Water Vapour 74,000 ppm

Assumptions

1. Hydrogen and Oxygen are present in the Fuel and Water in known ratios
2. Fuel O and Fuel H are released homogeneously from biomass even if the fuel burns inhomogeneously

Fuel O = a	8.22045
H2O O = b	2.97852
Fuel H = c	47.3392
H2O H = d	5.95674
Fixed Ratio a/c	0.17365
Fixed Ratio b/d	0.50002
Ratio ∑O/∑H	0.21013

Assumptions

1. Hydrogen and Oxygen are present in the Fuel and Water in known ratios
2. Fuel O and Fuel H are released homogeneously from biomass even if the fuel burns inhomogeneously

Fuel O = a	8.22045
H2O O = b	2.97852
Fuel H = c	47.3392
H2O H = d	5.95674
Fixed Ratio a/c	0.17365
Fixed Ratio b/d	0.50002
Ratio ∑O/∑H	0.21013

All three are simultaneously true

De-combustion

De-Combustion					
	Delete Air				
	Split H2				
Moles of elements Entrained with air	Remove air: CO_2, NAr+O, Mol Elements	Split Fuel H from H_2O, Mol Elements	g	Estimated ARAF Ultimate Analysis % mass	
0.1357	62.901	62.901	75.548	75.55	Carbon
71.3027	11.19897	8.2205	13.152	13.15	Oxygen
	53.29593	47.339	4.772	4.77	Hydrogen
	Water O >>	2.979	5.366	5.37	Moisture from Fuel
	Water H >>	5.957			
	0.060	0.060	0.194	0.19	Sulfur
	0.692	0.692	0.969	0.97	Nitrogen in Fuel
3.1675	-				Argon from Air
264.80	-				N_2 from Air
71.44 moles	128.15 moles	128.15 moles	100.00	100.00	
			Mass	%	

De-combustion

De-Combustion					
	Delete Air				
	Split H2				
Moles of elements Entrained with air	Remove air: CO_2, NAr+O, Mol Elements	Split Fuel H from H_2O, Mol Elements	g	Estimated ARAF Ultimate Analysis % mass	
0.1357	62.901	62.901	75.548	75.55	Carbon
71.3027	11.19897	8.2205	13.152	13.15	Oxygen
	53.29593	47.339	4.772	4.77	Hydrogen
	Water O >>	2.979	5.366	5.37	Moisture from Fuel
	Water H >>	5.957			
	0.060	0.060	0.194	0.19	Sulfur
	0.692	0.692	0.969	0.97	Nitrogen in Fuel
3.1675	-				Argon from Air
264.80	-				N_2 from Air
71.44 moles	128.15 moles	128.15 moles	100.00	100.00	
			Mass	%	

Check for a fuel moisture deficit or surplus

The HHV of this "fuel" is used in the denominator of the Efficiency calculation

Significance of Real-Time Fuel Analysis

The HHV can be calculated in real time as the fuel evolves

The CO_{2MAX} value can be calculated in real time

Significance of Real-Time Fuel Analysis

The HHV can be calculated in real time as the fuel evolves

The CO_{2MAX} value can be calculated in real time

The ratio of the oxygen provided by air to the total oxygen demand can be determined in real time [*StOxR*]

Significance of Real-Time Fuel Analysis

The HHV can be calculated in real time as the fuel evolves

The CO_{2MAX} value can be calculated in real time

The ratio of the oxygen provided by air to the total oxygen demand can be determined in real time [*StOxR*]

The stoichiometric volume of combustion gases can be calculated using StOxR.

From this the diluted volume of gases can be calculated using the Excess Air level.

The concentration of pollutants in that volume can be determined.

Significance of Real-Time Fuel Analysis

The HHV can be calculated in real time as the fuel evolves
The CO_{2MAX} value can be calculated in real time

The ratio of the oxygen provided by air to the total oxygen demand can be determined in real time [*StOxR*]

The stoichiometric volume of combustion gases can be calculated using StOxR. From this the diluted volume of gases can be calculated using the Excess Air level. The concentration of pollutants in that volume can be determined.

The mass of emissions can be reported more accurately per measurement interval.

Why is this an improvement?

Two **different approaches** can be made:

1. Assume the fuel burns and dries homogeneously
2. Assume this is not the case but that the Oxygen and Hydrogen are released from the fuel homogeneously

The Chemical Mass Balance assumptions provide an analysis that more **closely represents** what is actually happening in a solid fuel fire.

Fuel O = a	8.22045
H2O O = b	2.97852
Fuel H = c	47.3392
H2O H = d	5.95674
Fixed Ratio a/c	0.17365
Fixed Ratio b/d	0.50002
Ratio ∑O/∑H	0.21013

Why is this an improvement?

Two **different approaches** can be made:

1. Assume the fuel burns and dries homogeneously
2. Assume this is not the case but that the Oxygen and Hydrogen are released from the fuel homogeneously

The Chemical Mass Balance assumptions provide an analysis that more **closely represents** what is actually happening in a solid fuel fire.

Fuel O = a	8.22045	
H2O O = b	2.97852	
Fuel H = c	47.3392	
H2O H = d	5.95674	
Fixed Ratio a/c	0.17365	Fuel O to Fuel H
Fixed Ratio b/d	0.50002	Water O to Water H
Ratio ∑O/∑H	0.21013	Measured ∑O to Measured ∑H

Thank you!

Appreciations:

Staff and graduate students at:
The SeTAR Centre, Research Village, University of Johannesburg, Department of Geography, Environmental Management and Energy Studies, JHB, R.S.A.

Chinese University of Agriculture, College of Engineering, Beijing, China

Cape Peninsula University of Technology, Cape Town, R.S.A.

This work represents personal efforts and was not funded.

Stove making, Bishkek, Kyrgyzstan 2016

Stove testing lab, Haidian North, China 2016