Numerical Optimisation of Excess Air with Respect to Fibre-To-Shell Ratio during Incineration Process

www.serd.ait.ac.th/reric

Mohamed Harimi[*], **M.M.H. Megat Ahmad**[**], **S. M. Sapuan**[**]
and Azni Idris[***]
[*]Centre of Materials and Minerals -CMM
Universiti Malaysia Sabah
88999 Kota Kinabalu
Sabah
MALAYSIA
[**]Department of Mechanical and Manufacturing Engineering
Universiti Putra Malaysia
43400 Serdang
Selangor Darul Ehsan
MALAYSIA
[***]Department of Chemical and Environmental Engineering
Universiti Putra Malaysia
43400 Serdang
Selangor Darul Ehsan
MALAYSIA
e-mail: harimimo@ums.edu.my or harimi2000@hotmail.com

ABSTRACT

The incineration of palm oil wastes mainly fibre and shell is currently mixed randomly which makes the amount of air required to be difficult to control or to maintain and consequently, the control of flue gas emissions becomes the most difficult task. In this study, five different chemical compositions of fibre and shell were obtained from five different palm oil mills in Malaysia. With the existing of powerful software STANJAN code, the emissions of flue gases were computed using all the data from the five palm oil mills. The data output from those mills was analysed using analysis of variance (ANOVA) and the difference among the data output were found statically not significant, and thus, palm oil mill number three was selected as a base data. From the 24 chemical species, the optimisation was done based on CO_2, CO, and O_2 emissions only, following the Ambient Air Quality Malaysian Standard (AAQMS). The required amounts of excess air for different ratios of fibre-to-shell were computed, in addition, a mathematical model relating excess air to the percentage of fibre in the shell was developed. It was found that the percentage of excess air required for any ratio of fibre-to-shell in order to fulfil the requirement of AAQMS, varies from about 65% to 85%. The boiler operator can use more than 85% depending on the type of incinerator used, but the problem of increasing the heat loss and thus decreasing the thermal efficiency of the boiler is expected. Due to this reason a global optimisation is recommended, taking into account not only the CO emission but also the heat loss due to dry flue gas.

Keywords - Palm Oil Wastes, Fibre, Shell, Carbon Monoxide, Combustion Efficiency, Excess Air, Ratio of Fibre-To-Shell.

1. INTRODUCTION

In Malaysia, where many giant palm oil plantations and processing industries have been developed, researchers have dealt with energy conversion from the fibre and shell of the industry wastes as an alternative energy source [1]. They proved that the fibre and shell could be conventionally used as fuel for a steam boiler. The calculations have shown that oil wastes can generate more than enough energy to meet the energy demand of the palm oil mill. Another advantage of using the fibre and shell as a boiler fuel is that it helps to dispose these bulky materials which otherwise would contribute to environmental pollution. The ash from the combustion process is also found suitable for fertilizer for palm oil plantation. The incineration of palm oil waste requires regular operator intervention due to the change of the ratio of fibre-to-shell. Therefore the operator should adjust the air supply to maintain the desired heat output and optimum combustion conditions as the combustion progresses through its various stages, otherwise the air pollution takes place. A simple, low-cost way of optimizing combustion is to maintain the proper air to fuel ratio in the boiler operations [2]. Automatic heat output is possible by incorporating thermostatically controlled air valves, but these tend to produce high levels of air pollution as they cycle between full burn and minimal burn conditions [3]. That is the reason, why most of palm oil mills have problems in controlling properly air emissions in boiler, due to the non-homogeneity of the solid wastes even with installation of a sophisticated airflow device. The objective of this research is to optimize percentage of excess air with respect to fibre-to-shell ratio based on low CO emission, and thus high combustion efficiency.

2. RESEARCH METHODOLOGY

Some of the composition of palm oil wastes (POW) contained sulfur, and some others do not have or may be neglected. Even for the case of chlorine almost in all compositions of POW have no trace at all. The methodology used to optimise fibre-to-shell ratio is highlighted, based on five different POWs taken from five different palm oil mills.

2.1 Chemical Species Involved

Twenty-six species have been considered as a part of combustion products. In the case where sulfur is not present, therefore only 22 species will be a part of the system. Also as it was mentioned before, that chlorine, for most of the time is not present in the elemental chemical composition, so it means that the total species is just 24. In the case where both sulfur and chlorine are not present in the composition of SW, then only 20 species are involved in the combustion products. The list of chemical species involved in this research is listed in table 1, with 24 chemical species involved.

2.2 Chemical Composition of Fibre and Shell

Different compositions of fibre and shell have been obtained from five palm oil mills in Malaysia and the name of those mills are not mentioned for the sake of confidentiality. The chemical composition of fibre and shell from the five palm oil mills are listed in table 2.

Here under this section two different solid wastes generated from palm oil processing, including fibre and shell are used. The notation is given in table 3, which is helpful in the present analysis.

In the analysis, the new elemental chemical composition of the mixture (fibre and shell) is based on Eqs. (1)

$$m_T = \Sigma m_j \quad (j=1, 2) \tag{1}$$

$$m_i = (\Sigma\, m_{ij} \,.\, m_j) / m_T \quad (i = 1 \text{ to } 8) \tag{2}$$

where;

m_j : Mass of waste # j in the mixture.
m_{ij} : Mass fraction of element i for waste # j (for fibre j=1, for shell j=2)
m_i : Mass fraction of element i of the mixture.

The computation of the higher heating value (*HHV*) for the mixture is simply given in Eq. (3).

$$HHV = (\Sigma\, mj\, HHVj\,) / m_T \tag{3}$$

Table 1. Species and Elements Used

#	Species	Name	M_w
01	CO_2	Carbon Dioxide	44.01
02	CO	Carbon Monoxide	28.01
03	C	Carbon	12.01
04	CH_4	Methane	16.04
05	C_2H_2	Acetylene	26.04
06	C_2H_4	Ethylene	28.05
07	H_2O	Water	18.02
08	H_2	Hydrogen	02.02
09	OH	Hydroxyl Radical	17.01
10	HO_2	Hydroperoxy radical	33.01
11	H	Hydrogen atom	01.01
12	N_2	Nitrogen	28.01
13	NO	Nitric Oxide	30.01
14	NO_2	Nitrogen Dioxide	46.01
15	N_2O	Nitrous Oxide	44.01
16	N	Nitrogen atom	14.01
17	O_2	Oxygen	32.00
18	O	Oxygen atom	16.00
19	O_3	Ozone	48.00
20	NH_3	Ammonia	17.03
21	SO_2	Sulfur Dioxide	64.06
22	SO_3	Sulfur Trioxide	80.06
23	SO	Sulfur Monoxide	48.07
24	H_2S	Hydrogen Sulfide	34.08

M_w: Molecular weight

Table 2. Chemical Composition of Fibre and Shell from Five Palm Oil Mills

Mill #	1		2		3		4		5	
Element	Fibre	Shell	Fibre	Shell	Fibre	Shell	Fibre	Shell	Fibre	Shell
C	27.48	44.79	33.79	39.36	30.68	47.16	28.66	42.69	30.02	43.8
H_2	3.82	5.66	4.80	5.290	3.90	5.67	3.35	4.69	3.81	5.27
S	0.00	0.00	0.00	0.000	0.20	0.18	0.02	0.02	0.19	0.17
N_2	1.09	0.54	1.09	0.970	0.91	0.54	0.36	0.38	0.89	0.5
O_2	25.46	31.95	25.22	32.03	23.86	33.57	25.89	33.14	23.35	31.18
H_2O	39.39	12.96	32.06	18.44	35.00	10.00	40.00	15.00	36.4	16.4
Ash	2.760	4.10	3.04	3.91	5.45	2.88	1.8	4.2	5.34	2.68
HHV	10.64	17.50	11.94	15.13	11.69	18.05	9.82	15.96	11.43	16.77

HHV: Higher heating value of the fuel in MJ/kg.

Table 3. Notation Used for Fibre, Shell, and Mixture

Element		Fibre (m_f)	Shell (m_s)	Total (m_T)
Carbon	C	mf_1	ms_1	m_1
Hydrogen	H_2	mf_2	ms_2	m_2
Sulfur	S	mf_3	ms_3	m_3
Nitrogen	N_2	mf_4	ms_4	m_4
Oxygen	O_2	mf_5	ms_5	m_5
Chlorine	Cl_2	mf_6	ms_6	m_6
Moisture	H_2O	mf_7	ms_7	m_7
Ash		mf_8	ms_8	m_8

m_f, m_s, m_T: Mass of fibre and shell in the total mixture respectively.

2.3 STANJAN Code Software

Fast and efficient numerical programs are needed both for static calculations of the equilibrium composition of large chemical systems and for dynamic calculations involving the assumption of local thermodynamic equilibrium (LTE) [4,5]. At the present time, the most readily available and widely used programs of this type are the NASA [6] and STANJAN [7] equilibrium programs. In this research, STANJAN software has been chosen for the computation of chemical equilibrium species, because it is widely used software and also in comparison to NASA, STANJAN is more powerful [8]. Research done by Bishnu et al. [8], on the evaluation of the performance of STANJAN AND NASA CODES shows that test calculations have been made for the hydrogen-oxygen (H-O) and carbon-hydrogen-oxygen-nitrogen (C-H-O-N) systems with various combinations of constraints on the elements. The allowed domain of the constraints was determined and both interior and boundary points were investigated for several temperature and pressure conditions. The results showed that STANJAN is superior to NASA both in convergence and speed under all conditions investigated [8].

NASA [6] and STANJAN programs [7] use the method of Lagrange multipliers to determine the equilibrium composition of a chemical system by minimizing its Gibbs energy function subject to elemental constraints of the form [8]:

$$C_i = \sum_{j=1}^{n_s} a_{ij} \cdot N_j \qquad i=1,\ldots\ldots, n_c \tag{4}$$

where N_j is the number of moles of the j^{th} element in the system, a_{ij} is the number of atoms of the i^{th} element in the j^{th} species, n_s is the number of different species and n_c is the number of different elements in the system. In the following brief summary of the equations used in these calculations, we shall limit our considerations to gas-phase systems which obey the ideal gas equation of state Eq. (5).

$$p.V = M.R.T \tag{5}$$

where p is the pressure, V is the volume, T is the temperature, M is the mole number and R is the universal gas constant. For such a system, the dimensionless Gibbs energy function, , is given by:

$$\tilde{\mu} = \sum_{j=1}^{n_s} \tilde{\mu}_j \cdot N_j \tag{6}$$

where

$$\tilde{\mu}_j = \tilde{\mu}_j(T, p_j) = \tilde{\mu}_j^o(T) + \ln p_j \qquad j = 1, \ldots\ldots.., n_s \tag{7}$$

is the dimensionless Gibbs energy function of temperature T and partial pressure p_j in atmospheres for the species j , $\tilde{\mu}_j^o(T)$ is the dimensionless standard Gibbs energy function of temperature T for the species j. Minimizing the Gibbs energy function Eq. (6) subject to constraints Eq. (4) using the method of Lagrange multipliers leads to the result given in Eq. (8).

$$N_j = \frac{M}{p} \cdot \exp\left(-\tilde{\mu}_j^0 + \sum_{i=1}^{n_c} a_{ij} \cdot \lambda_i \right) \qquad j = 1, \ldots\ldots.., n_s \tag{8}$$

where λ_i is the dimensionless constraint potential [Lagrange multiplier] conjugate to the constraint C_i. Eq. (8) can, in turn, be substituted back into the constraint Eq. (4) to obtain a set of n_c transcendental equations which can be solved in conjunction with the equation of state Eq. (5) for the n_c constraint potentials and the mole number M. For systems which include a large number of species, n_c is much smaller than ns and solving for the n_c constraint potentials is much easier than solving for the n_s species concentrations using the method of equilibrium constants.

The data input to the software STANJAN takes into account the following data:

- Chemical composition in mole fraction or moles.
- Initial temperature and pressure.
- Final temperature and pressure (optional).
- Atoms present in the flue gas.
- Two constraints: constant pressure (pressure of the reactants is equal to the total pressure of the products) and constant Enthalpy (enthalpy of the reactants is equal to the enthalpy of products).
- List of the flue gases under study is given in table 1.

Data output from STANJAN code gives the initial state and equilibrium state of the pressure, temperature, volume, enthalpy, internal energy, and entropy. After that, the products of combustion come also into two parts initial state and final state in mole fraction and mass fraction.

2.4 Algorithm of Optimising Fibre-to-Shell Ratio

The optimisations take into account the ratio of fibre to shell (also the ratio of carbon to hydrogen can be considered), and the amount of excess air is included. The process of combustion took place at constant pressure and constant enthalpy (no heat loss, based on adiabatic flame temperature calculation) with a constraint on the maximum limit of CO limited to 9 ppmv by DOE [10]. Here in the following part a general algorithm summarizes the idea on how the optimisations are achieved:

Step 1: Fix a ratio of fibre to shell *F/S* or just % of fibre in shell (P_{fs}) (0:100, 20:80, 40:60, 50:50, 60:40, 80:20, and 100:0)

Step 2: Compute for a given ratio the new composition of the Biomass.

Step 3: Excess air used as percentage (0, 20, 40, 60, 80, 100, 120, and 150)

Step 4: For every excess air compute the stoichiometric and actual air.

Step 5: Compute the flue Gases (26 chemical species).

Step 6: Based on the environment standard [10], Convert the amount of *CO* at ambient temperature and pressure (*ATP*: 1 atm and 25 °C) corrected to 6% O_2.

Step 7: Locate the excess air at which the *CO* in *Step 6* should be less or equal to 9 ppmv based on environment regulatory [10] for a given P_{fs}.

Step 9: Correlate the data of CO_2, CO, and combustion efficiency $ç_c$ with an appropriate mathematical models.

Step 10: Locate the Optimum points of excess air at which CO should be less or equal to 9 ppmv using the data of *Step 6*.

Step 11: Memorize the optimum point (local) of excess air and compute the corresponding value of $ç_c$ using the mathematical models of step 9.
The combustion efficiency formula is based on Eq. (9), [11]:

$$ç_c = 100.\, y_1/(y_1 + y_2) \tag{9}$$

where:
$ç_c$: Combustion Efficiency in %.
y_1: Carbon Dioxide in mole fraction.
y_2: Carbon Monoxide in mole fraction.
$\Rightarrow P_{fs1} \longrightarrow PEA_1, ç_{c1}, H_{CL1}$ (optimum 1)

Step 12: Repeat *Step 1* until *Step 11*

Step 13: Final results, group all the optimum points found in one table.

3. RESULTS AND DISCUSSION

3.1 Main Results

The output from STANJAN code are given in table 4, but not for all the 24 chemical species, it includes only CO_2, CO, H_2O, H_2, NO, NO_2, N_2, and O_2. In the optimisation of fibre and shell, the chemical species needed are CO_2, CO, and O_2, and also the adiabatic flame temperatures are given in table 5.

Table 4. Output of Flue Gases from STANJAN Code

PEA	Chemical species	Fibre-to-Shell Ratio						
		0:100	20:80	40:60	50:50	60:40	80:20	100:0
0%	CO_2	1.35E-01	1.36E-01	1.36E-01	1.36E-01	1.36E-01	1.36E-01	1.36E-01
	CO	2.90E-02	2.63E-02	2.35E-02	2.20E-02	2.05E-02	1.73E-02	1.39E-02
	H_2O	1.32E-01	1.45E-01	1.60E-01	1.69E-01	1.77E-01	1.97E-01	2.20E-01
	H_2	4.78E-03	4.82E-03	4.80E-03	4.76E-03	4.70E-03	4.51E-03	4.19E-03
	NO	4.74E-03	4.32E-03	3.88E-03	3.64E-03	3.40E-03	2.89E-03	2.36E-03
	NO_2	1.02E-06	9.21E-07	8.14E-07	7.59E-07	7.02E-07	5.84E-07	4.64E-07
	N_2	6.73E-01	6.63E-01	6.53E-01	6.48E-01	6.41E-01	6.28E-01	6.12E-01
	O_2	1.25E-02	1.15E-02	1.05E-02	9.93E-03	9.34E-03	8.09E-03	6.75E-03
40%	CO_2	1.22E-01	1.21E-01	1.20E-01	1.19E-01	1.18E-01	1.17E-01	1.15E-01
	CO	2.07E-03	1.72E-03	1.38E-03	1.22E-03	1.06E-03	7.72E-04	5.21E-04
	H_2O	1.04E-01	1.15E-01	1.26E-01	1.33E-01	1.40E-01	1.55E-01	1.73E-01
	H_2	3.51E-04	3.29E-04	3.00E-04	2.83E-04	2.64E-04	2.23E-04	1.78E-04
	NO	5.45E-03	5.08E-03	4.68E-03	4.47E-03	4.24E-03	3.77E-03	3.27E-03
	NO_2	3.48E-06	3.35E-06	3.21E-06	3.13E-06	3.05E-06	2.87E-06	2.66E-06
	N_2	7.11E-01	7.03E-01	6.94E-01	6.89E-01	6.84E-01	6.72E-01	6.58E-01
	O_2	5.17E-02	5.11E-02	5.05E-02	5.02E-02	4.98E-02	4.91E-02	4.82E-02
80%	CO_2	9.87E-02	9.79E-02	9.69E-02	9.64E-02	9.58E-02	9.45E-02	9.29E-02
	CO	1.07E-04	8.80E-05	6.98E-05	6.12E-05	5.30E-05	3.81E-05	2.55E-05
	H_2O	8.42E-02	9.25E-02	1.02E-01	1.07E-01	1.13E-01	1.26E-01	1.41E-01
	H_2	2.31E-05	2.14E-05	1.93E-05	1.81E-05	1.69E-05	1.41E-05	1.12E-05
	NO	3.13E-03	2.91E-03	2.68E-03	2.56E-03	2.43E-03	2.16E-03	1.87E-03
	NO_2	4.28E-06	4.13E-06	3.97E-06	3.87E-06	3.78E-06	3.56E-06	3.32E-06
	N_2	7.28E-01	7.22E-01	7.14E-01	7.10E-01	7.06E-01	6.96E-01	6.84E-01
	O_2	8.45E-02	8.38E-02	8.30E-02	8.26E-02	8.21E-02	8.10E-02	7.98E-02
120%	CO_2	8.20E-02	8.14E-02	8.08E-02	8.04E-02	8.00E-02	7.90E-02	7.80E-02
	CO	6.70E-06	5.50E-06	4.38E-06	3.84E-06	3.34E-06	2.41E-06	1.62E-06
	H_2O	7.01E-02	7.71E-02	8.51E-02	8.96E-02	9.44E-02	1.05E-01	1.18E-01
	H_2	1.86E-06	1.72E-06	1.56E-06	1.47E-06	1.37E-06	1.16E-06	9.22E-07
	NO	1.59E-03	1.48E-03	1.37E-03	1.30E-03	1.24E-03	1.11E-03	9.61E-04
	NO_2	4.07E-06	3.93E-06	3.78E-06	3.70E-06	3.61E-06	3.42E-06	3.20E-06
	N_2	7.40E-01	7.34E-01	7.28E-01	7.24E-01	7.20E-01	7.12E-01	7.02E-01
	O_2	1.06E-01	1.06E-01	1.05E-01	1.04E-01	1.04E-01	1.03E-01	1.01E-01
150%	CO_2	7.27E-02	7.23E-02	7.17E-02	7.14E-02	7.11E-02	7.04E-02	6.95E-02
	CO	9.52E-07	7.84E-07	6.25E-07	5.50E-07	4.78E-07	3.47E-07	2.34E-07
	H_2O	6.22E-02	6.85E-02	7.57E-02	7.97E-02	8.40E-02	9.37E-02	1.05E-01
	H_2	3.19E-07	2.97E-07	2.70E-07	2.54E-07	2.38E-07	2.01E-07	1.62E-07
	NO	9.47E-04	8.84E-04	8.16E-04	7.81E-04	7.43E-04	6.64E-04	5.79E-04
	NO_2	3.69E-06	3.58E-06	3.44E-06	3.37E-06	3.30E-06	3.13E-06	2.93E-06
	N_2	7.45E-01	7.41E-01	7.35E-01	7.32E-01	7.28E-01	7.20E-01	7.11E-01
	O_2	1.18E-01	1.18E-01	1.17E-01	1.16E-01	1.16E-01	1.15E-01	1.13E-01

Table 5. Adiabatic Flame Temperature (K)

Fibre to Shell ratio	Percentage Excess Air							
	0	20	40	60	80	100	120	150
0:100	2424	2299	2139	1982	1844	1726	1624	1496
20:80	2399	2274	2114	1960	1826	1709	1609	1483
40:60	2371	2245	2086	1934	1802	1689	1592	1469
50:50	2355	2229	2070	1920	1790	1678	1582	1461
60:40	2338	2212	2053	1905	1777	1667	1572	1452
80:20	2299	2171	2014	1871	1747	1641	1549	1432
100:20	2252	2123	1969	1831	1712	1610	1521	1409

3.2 Statistical Analysis

Statistical test is done based on the incineration of fibre and shell, where N_2, O_2, CO_2, and CO are considered. Also combustion efficiency is tested based on Eq. (9) for all the ratio of fibre-to-shell in order to reinforce the conclusion. First the data of N_2, O_2, CO_2, and CO are deduced from the total output of STANJAN code, but it is not presented in this paper due to the large file. The results of the statistical test applied (ANOVA-One Way) are presented in Table 6. The amount of SO_2 is not presented because not all fibre and shell got sulfur, even though the amount of SO_2 and SO_3 are very small and in all cases negligible.

From the statistical table, at $df = 4$ for the between group and at $df = 35$ for the within group, the F_{crit} is between 2.61 and 3.83 at any level of significance. The F_{comp} in Table 4 is less than F_{crit}, therefore the differences of flue gases N_2, O_2, CO_2 and CO for shell and fibre from the five palm oil mills are statistically not significant at any level. Palm oil mill number three is selected because it contains sulfur and is almost similar to palm oil mill five, whereas palm oil mill four has a very small amount of sulfur and similar to palm oil mill one and two.

Table 6. Statistical Test ANOVA-1-Way for Major Flue Gases from 5 Mills

Flue Gas	Source	*df*	*SS*	*MS*	F_{comp}
N_2 Shell	*BG*	4	0.00063	0.00016	0.3199
	WG	35	0.017231	0.000492	
N_2 Fibre	*BG*	4	0.002424	0.00061	0.7343
	WG	35	0.02889	0.000825	
O_2 Shell	*BG*	4	0.000008	1.9767E-06	0.001177
	WG	35	0.058796	0.00168	
O_2 Fibre	*BG*	4	0.00004	0.00001	0.005893
	WG	35	0.059903	0.001712	
CO_2 Shell	*BG*	4	0.000431	0.00011	0.08056
	WG	35	0.04684	0.001338	
CO_2 Fibre	*BG*	4	0.000777	0.00019	0.13419
	WG	35	0.05067	0.001448	
CO Shell	*BG*	4	314.573	78.6433	0.009259
	WG	35	297271.884	8493.4824	
CO Fibre	*BG*	4	162.103	40.5258	0.01793
	WG	35	79088.1953	2259.6628	

BG: Between group *WG*: Within group *df*: Degree of freedom *SS*: Sum of squares
MS: Mean square F_{comp}: Statistical F-test computed using ANOVA-1way

3.3 Combustion Efficiency

The computation of combustion efficiency $_c$ is based on Eq. (9), therefore the results obtained are given in table 7. Before mentioning which combustion efficiency is appropriate for the environment side, the amount of CO should be converted to CO emission following the Malaysian Ambient Air Quality Guidelines at ambient temperature and pressure of 25 °C and 1 atm. The maximum level of CO according to DOE [10] should be 9 ppmv (corrected to 6% of O_2 in the flue gas). In some other countries like for example Canada, the maximum level of CO is limited to 50 ppmv corrected to 3% O_2 at standard temperature and pressure (*STP*) of 0 °C and 1 atm [12]. In comparison to the Malaysia Standard, after converting the CO from *STP* to *ATP* and also corrected to 6% of O_2 as shown in table 8 , the maximum limit of CO in Malaysia is much more less than maximum limit of CO in Canada. This indicates that the Malaysian Ambient Air Quality Guidelines are environmentally accepted worldwide. The conversion of CO to ambient temperature and pressure [*ATP]* is computed using Eqs. (10) and (11) based on ideal gas law.

$$CO_{6\%} = [15/(21 - O_{2act})]\, CO_{act} \tag{10}$$

$$CO_{ATP} = CO_{6\%}\,(298.15/T_f) * (1 - y_7) \tag{11}$$

Where, $CO_{6\%}$ is the percentage of CO by volume corrected to 6% of O_2, CO_{act} is actual percentage of CO by volume, CO_{ATP} percentage by volume of CO at 25 °C and 1 atm, O_{2act} actual percentage O_2 by volume, T_f represents flame temperature at which the actual CO is recorded in the present case all the flue gases was computed at adiabatic flame temperature, and y_7 is fraction by volume of water vapour in the flue gas.

Table 7. Results of Combustion Efficiency

Fibre to Shell ratio	Percentage Excess Air							
	0	20	40	60	80	100	120	150
0:100	82.3713	93.9470	98.3367	99.5777	99.8913	99.9708	99.9918	99.9987
20:80	83.7727	94.7309	98.6030	99.6499	99.9102	99.9759	99.9932	99.9989
40:60	85.2980	95.5410	98.8633	99.7189	99.9281	99.9807	99.9946	99.9991
50:50	86.1104	95.9530	98.9896	99.7518	99.9366	99.9830	99.9952	99.9992
60:40	86.9546	96.3660	99.1121	99.7833	99.9447	99.9852	99.9958	99.9993
80:20	88.7529	97.1867	99.3429	99.8416	99.9597	99.9892	99.9970	99.9995
100:0	90.6817	97.9701	99.5472	99.8921	99.9726	99.9926	99.9979	99.9997

Table 8. Carbon Monoxide Emission at 1 atm and 25 °C (ppmv)

Fibre to Shell ratio	Percentage Excess Air							
	0	20	40	60	80	100	120	150
0:100	2213	704	185	45.44	11.36	2.9877	0.8212	0.1278
20:80	1997	604	154	37.35	9.35	2.4536	0.6753	0.1054
40:60	1774	502	123	29.69	7.44	1.9534	0.5388	0.08421
50:50	1654	451	109	26.08	6.53	1.7140	0.4730	0.07419
60:40	1537	401	94.79	22.67	5.66	1.4849	0.4118	0.06457
80:20	1287	304	69.14	16.32	4.08	1.0752	0.2980	0.04702
100:0	1026	214	46.71	10.94	2.74	0.7241	0.2010	0.03182

It appears from table 8, that the maximum limit of CO (9 ppmv) at any ratio of fibre to shell is located at an excess air above 60%, therefore all the mathematical modelling use the excess air of 40% and above, and thus minimizing the error of correlation related to the first two values of excess air 0% and 20%. The mathematical modelling for the concentration of CO_2 and CO chosen to fit the data has the following forms:

For CO_2: $$y_1 = a \cdot PEA^b \quad (12)$$

For CO: $$y_2 = c \cdot PEA^d \quad (13)$$

Where, *a*, *b*, *c*, and *d* are functions related to the percentage of fibre in the Shell, given in table 9, and *PEA* refers to the percentage excess air. For the mathematical modelling of carbon monoxide emission at *ATP*, the data in table 8 are used, and the following mathematical model has been selected:

$$CO_{ATP} = \alpha \cdot e^{(\beta \cdot PEA)} \quad (14)$$

Where; CO_{ATP} carbon monoxide evaluated at *ATP* condition (table 8), α and β are parameters related to percentage of fibre in the shell given in table 10.

Table 9. Numerical Data Used in Eqs. (19) and (20)

F/S	*a*	*b*	*c*	*d*	r^2 (CO_2)	r^2 (CO)
0:100	0.5357	-0.3920	5973062.23	-5.7566	0.98	0.97
20:80	0.5270	-0.3901	5062667.21	-5.7632	0.98	0.97
40:60	0.5212	-0.3896	4089764.66	-5.7665	0.98	0.97
50:50	0.5093	-0.3857	3655564.05	-5.7704	0.98	0.97
60:40	0.4975	-0.3819	3170134.51	-5.7702	0.98	0.97
80:20	0.4966	-0.3840	2304717.28	-5.7715	0.98	0.97
100:0	0.4793	-0.3796	1545252.35	-5.7711	0.98	0.97

r^2 (CO_2) and r^2 (CO) are correlation factors for CO_2 and CO respectively.

Table 10. Numerical Data Used in Eq. (21)

F/S	α	β	r^2
0:100	2.4146E+03	-6.6234E-02	0.999
20:80	2.0009E+03	-6.6292E-02	0.999
40:60	1.5920E+03	-6.6273E-02	0.999
50:50	1.4053E+03	-6.6310E-02	0.999
60:40	1.2196E+03	-6.6297E-02	0.999
80:20	8.8169E+02	-6.6276E-02	0.999
100:0	5.9168E+02	-6.6233E-02	0.999

r^2 correlation factor for CO_{ATP}

3.4 Optimizations

The optimisation focus on the environmental issue mainly related to CO emission. It was stated before that the maximum amount of CO emitted at *ATP* condition is 9 ppmv [10]. To minimize the error, and instead of doing interpolation of the data, the mathematical models obtained are correlated, and all the best curve fittings are obtained with all correlation factors above 0.96. From Eq. (14) the best excess air with respect to a given ratio of fibre to shell is obtained using Eq. (15).

$$PEA = (2.3026/\beta) \cdot \mathrm{Log}\,(50/\alpha) \quad (15)$$

When applying Eq. (15) with the help of the data from table 10, the data obtained are substituted into Eqs. (9), (12) and (13) corresponding to the parameters η_c, y_1, and y_2 respectively. The results obtained are locally representing for every ratio of fibre-to-shell, and its corresponding value of excess air are listed in table 11.The above data can be used as a reference for the best fibre-to-shell ratio, its corresponding value of excess air, and thus CO emissions are environmentally acceptable level. The percentage of excess air with respect to the percentage of fibre in shell, P_{fs} is highly correlated using quadratic equation of correlation coefficient of about 1 (0.9999) given in Eq. (16). In the same way, the percentage of fibre in shell P_{fs} with respect to the percentage of excess air, *PEA* is also highly correlated using quadratic equation of correlation coefficient of about 1 (0.9997) given in Eq. (17).

$$PEA = -9.4118\text{ E-04}\, P_{fs}^{2} - 0.11623\, P_{fs} + 84.338 \tag{16}$$

$$P_{fs} = -0.0993\, PEA^{2} + 10.001\, PEA - 135.68 \tag{17}$$

Eq. (16) can be used to find for any percentage of fibre in the shell, its corresponding value of excess air or in the opposite way using Eq. (17). Both equations are very useful to avoid any interpolation needed in using the data of table 11.

Table 11. Local Data Optimisations

F/S (Ratio)	*PEA* (%)	y_1 (mole faction)	y_2 (mole fraction)	η_c (%)
0:100	84.43	0.0941315	4.8543E-05	99.948457
20:80	81.52	0.0946731	4.8908E-05	99.948367
40:60	78.09	0.0954222	4.9894E-05	99.94774
50:50	76.17	0.0957568	5.0618E-05	99.947167
60:40	74.05	0.0961217	5.1706E-05	99.946236
80:20	69.17	0.0976064	5.5403E-05	99.943271
100:0	63.20	0.0993242	6.2644E-05	99.936969

4. CONCLUSION

Form this study, the percentage of excess air with respect to fibre-to-shell ratio has been optimised, and it has been found that for the fibre-to-shell ratio of 0:100, 20:80, 40:60, 50:50, 60:40, 80:20, and 100:0, their corresponding percentage of excess air should be 85, 82, 78, 76, 74, 69, and 63% respectively. The required amount of excess air can be also computed using a quadratic equation with percentage of fibre in the shell taken as an independent variable.

A global optimisation is highly recommended, taking into account the combustion efficiency and thermal efficiency, from which the best optimum point related to excess air and ratio of fibre-to-shell can be computed.

5. NOMENCALTURE

ATP	Ambient Temperature and Pressure.	
a, b	Parameters related to the percentage of fibre in the shell for CO_2 correlation with respect to the percentage of excess air.	
c, d	Parameters related to the percentage of fibre in the shell for CO correlation with respect to the percentage of excess air.	
$CO_{6\%}$	Carbon monoxide corrected to $_{6\%}$ of $O_{2.}$	% by volume
CO_{ATP}	Carbon monoxide converted to ATP condition.	% by volume
df	Degree of freedom used in the analysis of variance one-way.	
F/S	Fibre-to Shell Ratio.	

F_{compa}	F-test computed in the analysis of variance one-way.	
F_{crit}	F-test critical deduced from statistical tables of the anlysis of variance one-way.	
HHV	Higher Heating Value of the mixture fibre and shell.	kJ/kg of mix.
HHV_j	Higher Heating Value of the waste j.	kJ/kg of *j*
m_i	Mass fraction of element i of the mixture fibre and shell.	kg of *i* / kg of mix.
m_{ij}	Mass fraction of element I in the waste j.	kg of *i* / kg of *j*
m_j	Mass fraction of waste j in the mixture.	kg of *j* / kg of mix.
m_T	Total mass of waste including fibre and shell.	kg of mix.
PEA	Percentage of Excess Air.	%
P_{fs}	Percentage of fibre in shell.	%
T_f	Adiabatic flame temperature.	K
y_k	Mole fraction of the chemical component k in the flue gas.	
á â	Paramenters related to P_{fs} for CO correlation at ATP condition.	
K_c	Combustion efficiency.	%

Subscript:

i = 1 to 8 (table 3).
j = 1, 2 for fibre and shell respectively.
k = 1 to 24 (table 1).

6. REFERENCES

[1] Mahlia, T. M. I.; Abdulmuin, M. Z.; Alamsyah, T. M. I.; and Mukhlishien, D. 2001. An Alternative Energy Source from Palm Wastes Industry for Malaysia and Indonesia. *Energy Conversion and management* 42 (2001), 2109-2118.

[2] Christopher, R. and Tony, T. 2002. Reduce Fuel Costs - Use the Proper Air-to-Fuel Ratio in Boiler Combustion. *Steam Digest 2002.* Alliance To Save Energy: U.S. Department of Energy, 37-38.

[3] DEH 2002. Review of Literature on Residential Firewood Use, Wood-Smoke and Air Toxics. *Technical Report No. 4*, Department of the Environment and Heritage (DEH), Australia. http://www.deh.gov.au index.html

[4] DeGroot, S.R. and Mazur, P. 1962. *Non-Equilibrium Thermodynamics.* North-Holland Publisher, Amsterdam.

[5] Williams, F.A. 1985. *Combustion Theory.* Addison-Wesley, New York.

[6] Gordon, S and McBride, B. J. 1994. Computer program for calculation of complex chemical equilibrium compositions and applications. *NASA* Reference, Publication 131.

[7] Reynolds, W.C. 1986. STANJAN Program: The Element Potential Method Chemical Equilibrium Analysis. Thermosciences Division, Department of Mechanical Engineering Stanford University, California.

[8] Bishnu, P.S.; Hamiroune, D.; Metghalchi, M.; and Keck, J.C. 1997. Constrained-Equilibrium Calculations for Chemical Systems Subject to Generalized Linear Constraints using the NASA and STANJAN Equilibrium Programs. *Combust. Theory Modelling* 1, 295–312.

[9] Senmartin, D. 2005. Water Resources Management, Environment and Development. Country Reporting on MDG7: Ensuring Environmental Sustainability. Washington D.C. http:/www.developmentgateway.org

[10] DOE 2003. A guide to Air Pollutant Index in Malaysia. Ministry of Natural Resources and Environment.

[11] Brunner, C. R. 1993. *Hazardous Waste Incineration, 2nd Ed.* McGraw-Hill, Inc. New York.

[12] Dockrill, P. and Friedrich, F. 2001. Amélioration de l'efficacité énergétique des Systemes de Chauffage. Report by Federal Industrial Boiler Program, CANMET Energy Technology Centre, Natural Resources Canada.