Estimating Furnace Combustion Temperatures and Heat Losses in Boiler Flues

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RINGKASAN

Industri pengilangan minyak sawit menggunakan bahanapi pepejal dari sisa sawit untuk memanaskan 'dandang', bagi penjanaan kuasa 'terma' dan 'motive'. Artikel ini menggariskan satu cara bagi menganggar suhu pembakaran dan kehilangan haba dalam gas 'flue' dari 'dandang' kilang minyak sawit dibawah keadaan beberapa jenis bahanapi. Kesan-kesan penggunaan kadar angin berlebihan yang berbeza juga diterangkan.

INTRODUCTION

The palm oil milling industry uses palm waste solid fuels (fibre, shells and to a lesser extent, empty fruit bunches or EFB) to fire its boilers for thermal and motive power generation. Exact descriptions of boiler behaviour and performance are difficult, if not impossible, to formulate due to the lack of a comprehensive fuel data bank and that in practice, fuel and other operational characteristics are highly variable quantities. Nevertheless, for operational needs, approximations are usually good enough provided we incorporate the main governing relationships in our system description.

This paper describes a method to estimate combustion temperatures and sensible heat (or, enthalpy) losses in flue gases from palm oil mill boilers under various fuel conditions. The effects of using different excess air ratios are also summarized.

BASIC FUEL CHARACTERISTICS

Given the highly variable characteristics of palm waste solid fuels, it is not surprising that many different figures have been quoted in the literature IRSIA (1955), Maycock J.H (1985), Shafii, A.F. *et al*., (1986). To the author's knowledge, only one set of ultimate analysis data has been reported (Shafii, A.F. *et al.*, 1986). Using these references, a table listing the Gross Calorific Values (GCV) of dry fuel may be drawn up as shown in *Table 1*. The Net Calorific Values (NCV) for any fuel can then be calculated using the relation,

$$NCV = GCV\,(1-x) - 1055\,[9H\,(1-x) + x] \qquad (1)$$

where,

x is moisture content,
H is hydrogen composition in dry fuel, and
1055 is the latent heat of steam at 60°F, in BTU/lb.

Tables 2 and *3* list the composition of such fuels and their ash content. Clearly, palm waste fuels are characterized by high Volatile Matter (VM), low Fixed Carbon (FC) and relatively high ash contents. Ash is the residue left when all organic matter have been burnt away. The mineral matter content of the fuel, from which ash is derived, is usually 10% to 15% higher than ash content. Ash and moisture therefore, comprise the non-combustible or inert elements in a given mass of sampled fuel. Moisture, in particular, is troublesome, as we can see later in the combustion temperature calculations. Not only moisture has no calorific value, it also absorbs heat in being vaporized during combustion. These proximate characteristics along with the fuel specific handling requirements are enough arguments to say that

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TABLE 1. AVERAGE GROSS CALORIFIC VALUES OF DRY FUEL (kcal/kg)

Study	Empty Fruit Bunch	Fibre	Shell
Unilever	–	4388	4960
Mongana	4350	4825	4975
Nordanal	4630	4906	4880

TABLE 2. PALM WASTE FUEL ANALYSIS (wt. percent moisture free basis)

Proximate Analysis	Empty Fruit Bunch	Fibre	Shell
Volatile Matter	75.7	72.8	76.3
Fixed Carbon (Difference)	17.0	18.8	20.5
Ash	7.3	8.4	3.2
Total	100.0	100.0	100.0
Ultimate Analysis			
Hydrogen	6.3	6.0	6.3
Carbon	48.8	47.2	52.4
Sulphur	0.2	0.3	0.2
Nitrogen	0.7	1.4	0.6
Oxygen (by difference)	36.7	36.7	37.3
Ash	7.3	8.4	3.2
Total	100.0	100.0	100.0

TABLE 3. ASH COMPOSITION (wt. percent)

	Empty Bunch	Fibre	Shell
SiO_2	34.7	63.2	65.4
Al_2O_3	1.2	4.5	2.1
Fe_2O_3	1.8	3.9	3.3
CaO	3.3	7.2	3.1
MgO	2.9	3.8	3.2
Na_2O	0.8	0.8	0.5
K_2O	40.1	9.0	12.7
TiO_2	0.1	0.2	0.1
P_2O_5	2.5	2.8	3.3
SO_3	8.0	2.8	3.2
CO_2	0.1	2.2	3.8
Total	99.5	100.4	100.7

conventional furnace and boiler designs must be radically adapted if they are to offer high quality performance to the industry.

Ultimate compositions of C, H and O are in the typical range for cellulosic fuels (for instance, wood and baggase). Sulphur content is relatively low and it is neglected in subsequent calculations. Sulphur is normally oxidized to SO_2 and SO_3 but in the absence of oxygen, H_2S is usually formed.

The ash analysis indicates the relative compositions of eleven different compounds or oxides. EFB, apparently, has lower silicate but high potash contents. Fibre and shell ashes are characterized by high silicates. The iron oxides usually fuse with the silicates to form clinkers although in practice, when burning EFB, more clinkers are observed probably due to presence of extraneous foreign matter (sand, laterites, *etc.*) accompanying the bunches.

COMBUSTION TEMPERATURE ESTIMATION

For all intents and purposes, the chemical reactions of interest are listed in *Table 4*. In this paper, complete carbon combustion is assumed although a high degree of CO formation can contribute to significant heat losses (loss in potential heat release). Thus, in other industries the CO sensor increasingly finds itself being used to monitor furnace combustion efficiencies as part of an overall boiler control strategy. Heat contributions from sulphur combustion in palm waste fuels approximate to only 0.6% and hence, can be neglected.

Stoichiometrically therefore, 2.67 pounds of C will require 1.00 pound of O_2 to form 3.67 pounds of CO_2. Similarly, one pound of H_2 will require eight pounds of O_2 to form nine pounds of water. Since air is 76.9:23.1 by weight N_2 to O_2 (or, 20.8:79.2 by volume), each pound of O_2 required will bring with it (76.9/23.1) weight of ambient N_2. We could determine the weight and volume of theoretical air required per unit weight of dry fuel (α_1, α_2, say) and also find the weight and volume of water formed (β_1, β_2, say).

In practice, excess air is used to ensure complete combustion and fuels are far from dry. Assuming *r* to be the ratio of air to that theoretically required, we then proceed to determine the following (per unit weight of fuel basis):

1. Weight of air used , W_a
2. Volume of air , V_a
3. Weight of the gaseous products of combustion , W_g
4. Volume of the gaseous products of combustion , V_g
5. Weight of the flue gases on a dry basis , W_{gd}
6. Volume of the flue gases on a dry basis , V_{gd}

It can be shown that the following expressions are applicable to the combustion of wet fuels under consideration,

TABLE 4. CHEMICAL REACTIONS DURING COMBUSTION*

Combustible	Stoichiometry		Heat Release (BTU/lb)
Carbon	$C + O_2$	CO_2	14 500
Hydrogen	$2H_2 + O_2$	$2H_2O$	62 000
Sulphur	$S + O$	SO_2	4 000
Carbon Monoxide	$2CO_2 + O_2$	$2CO_2$	10 000
Carbon to Carbon Monoxide	$2C + O_2$	$2CO$	4 400
Methane (for comparison)	$CH_4 + 2O_2$	$CO_2 + 2H_2O$	23 000

*Skoglund, 1982.

$$W_a = \alpha_1 (1-x) r \quad (2)$$

$$V_a = \alpha_2 (1-x) r \quad (3)$$

$$W_g = \alpha_1 (1-x) r + 1 \quad (4)$$

$$V_g = \alpha_2 (1-x) r + \alpha_3 + \alpha_4 \quad (5)$$

where α_3, α_4 are terms due to the O_2 present in the fuel, the amount of water formed less the amount of O_2 required to form the water

$$W_{gd} = W_g - \beta_1 (-x) - x \quad (6)$$

$$V_{gd} = V_a - \alpha_5 \quad (7)$$

where α_5 is a resultant term after considering the gaseous products of combustion less any water present.

From these results, the composition of the flue gases is easily determined and the variation of CO_2 content with excess air ratio elucidated.

Now, if we assume that the heat released due to combustion are transferred to the gases passing from the furnace to the boiler proper, the combustion temperature can then be estimated. Any heat losses due to unburnt fuel and radiation in the furnace area can be accounted for by introducing simple proportionality factors, γ_1 and γ_2 respectively.

Since the calorific values and all other heat quantities have been expressed with reference to 32°F, it is necessary to accommodate for the energy already stored in the fuel and combustion air, at the ambient temperature t_a°F.

Thus per unit weight of fuel, the heat taken up by the gaseous products of combustion is given by,

$$\int_{32}^{t_a} 1 . c_f \, dt + \int_{32}^{t_a} w_a . c_a \, dt + \gamma_1 \gamma_2 (NCV) = \Sigma \int_{32}^{T} W_i . c_i \, dt \quad (8)$$

where W_i = weight of each of gaseous products of combustion per lb. of fuel.

c_i = specific heat of each of the gaseous products

The specific heats c_f, c_a, c_i are functions of temperature but using the mean specific heats over the temperature ranges encountered are usually acceptable thus, Eqn. (8) becomes

$$[c_f + w_a . c_a] [t_a - 32] + \gamma_1 \gamma_2 (NCV) = [\Sigma W_i c_i]_{32}^{T} (T - 32) \quad (9)$$

(NCV) is set, γ_1, γ_2 are chosen based on experience (around 0.98 to 0.99) and tabulated values of $[c_i]_{32}^{t}$ may be derived from literature (Habif, N., 1933). In this exericse, the cubic spline interpolation routine (Shafii, A.F., 1986) has been used to achieve rapid convergence to the required combustion temperature T. Alternatively a simple linear interpolation by hand may be used.

HEAT LOSSES ESTIMATION

Although the NCV expression in Eqn. (1) already reflects upon the heat losses due to water vapour, the most important of the losses is that due to the sensible heat of the flue gases. This amount is readily determined since for a given x and r, the composition of the flue gases and their mean specific heats are known.

DISCUSSION OF RESULTS

In the computation of combustion temperatures and flue gas heat losses, the following assumptions have been made.

1. Average gross calorific values from *Table 1* are used. Thus,

$$GCV_{shell} = 4905 > GCV_{fibre}$$
$$= 4705 > GCV_{FFB} = 4490$$

2. 1%–2% losses are allocated to unburnt fuels and radiation heat losses. These are embodied into the values of γ_1 and γ_2 respectively. However, in the combustion of the available solid fuel, complete combustion is assumed *i.e.* no CO formed.

3. Combustion stoichiometry is based on the ultimate compositions in *Table 2*. Since the contributions due to fuel S and N are insignificant, they are neglected.

4. The mean specific heats and densities of gaseous combustion products (N_2, O_2, H_2O and CO_2) and fuel over ambient temperatures to combustion temperatures are obtained from literature (see *Table 5*).

There are various ways to present the results of this exercise. To compare with typical industrial fuels, it is decided to plot, for each palm waste fuel and a typical fibre/shell mix.

- CO_2, O_2 content in flue gases (on dry basis) as a function of % excess combustion air used
- flue gas heat losses (as % of heat input) at different stack temperatures as a function of % excess combustion air used
- combustion or furnace temperatures as a function of % combustion air used

To reflect practical situations, the following fuel moisture contents are assigned:

EFB	@ 63.0%	moisture
Fibre	@ 36.4%	moisture
Shell	@ 16.4%	moisture

Oil content in each of these fuels will alter the individual GCVs. Since the GCVs of dry fuel used are the averages of literature values, their reliability should be taken with the reported oil contents (dry basis), *viz.*,

EFB	@ 0 – 5%	oil
Fibre	@ 0 – 10.4%	oil
Shell	@ 0 – 1%	oil

CO_2 and O_2 Contents

Figure 1 summarizes the CO_2 and O_2 contents in flue gases when compared to other common industrial fuels. Palm waste fuels are shown to give rise to higher CO_2 content than other fuels. The behaviour is closer to that of bituminuous coal. *Figure 1* also indicates that the O_2 content is less sensitive to the firing of different or mixed fuels at the same % excess combustion air used. Thus, in situations where the fuel is changed frequently, or, where mixed fuels are used, control by O_2 measurement may be preferable.

It is also interesting to note the fuel air ratios required for complete combustion. These are basically determined by fuel chemical composition and vary with % excess air used. The theoretical weight air-to-fuel ratios calculated are:

EFB	@ 2.30
Fibre	@ 3.77
Shell	@ 5.53

Significantly more air is required for shell is readily explained by its higher C content (52.4%). Increased O_2 demand will increase the N_2 into the system by a factor of 76.85/23.15 (by weight) and correspondingly also affects flue gas heat losses.

Flue Gas Heat Losses

Figures 2 and *4* incorporate the information in *Figure 1* and relating this to flue gas heat losses at different stack exit temperatures.

Losses are expressed as percentages of total heat input in fuel and air (NCV + heat from ambient conditions) and are shown to be considerably significant. The losses are, of course, higher with increasing stack temperatures (values for 100°C to 400°C are shown) and vary directly with % excess combustion air used.

Figure 3 and *4* are therefore useful to palm oil mill boiler operators if they are interested in a quick estimation of flue gas heat losses which affect boiler efficiencies. First, the CO_2 or O_2

TABLE 5. THERMAL AND MASS PROPERTIES USED

Substance	Specific Heat (kcal/kg°C)	Density (lb/ft^3)
CO_2	0.256 – 0.330	0.1234
H_2O	0.577 – 0.717	0.0502
N_2	0.26 – 0.278	0.0784
CO	0.26 – 0.28	0.0780
O_2	0.227-0.243	0.0892
Fibre, Shell	0.30	Not used

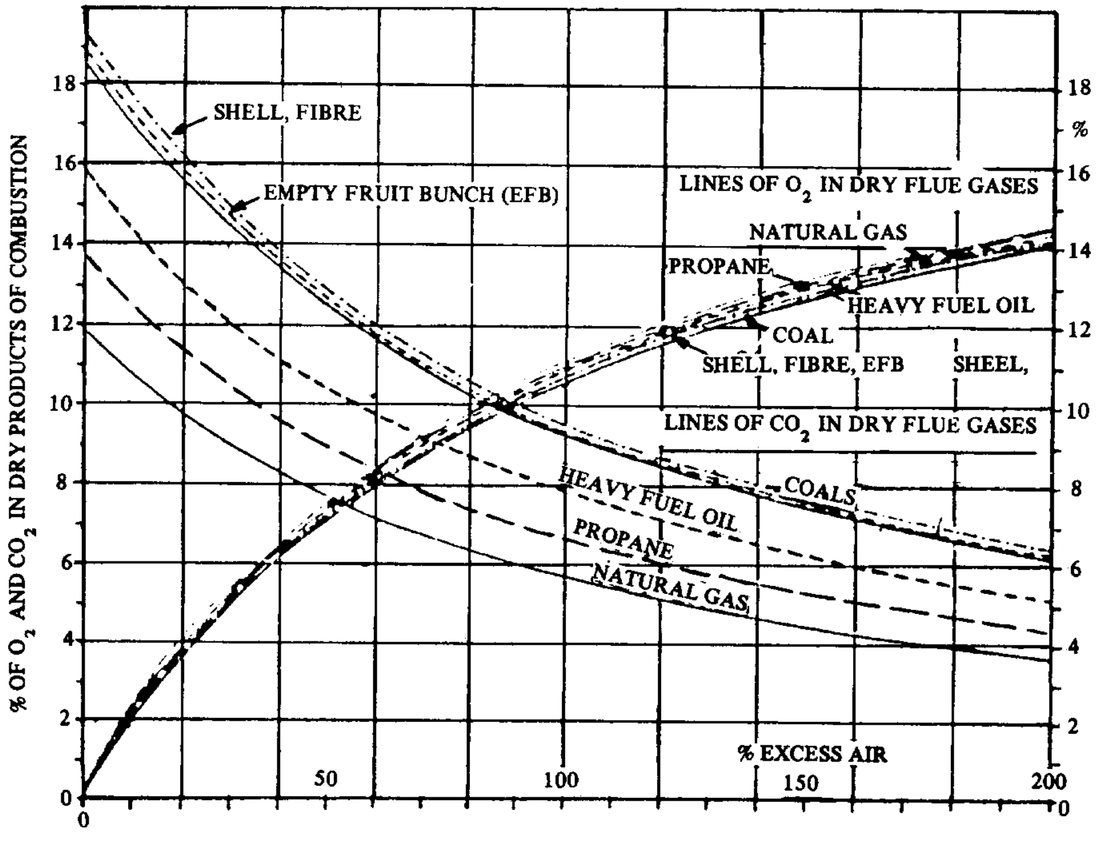
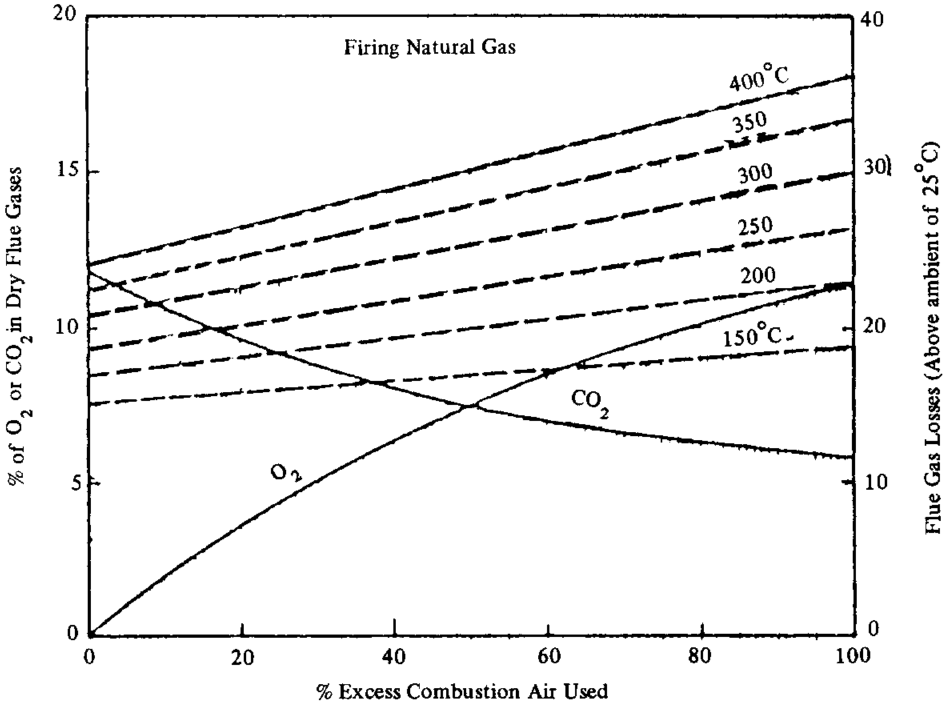


Figure 1. O_2 and CO_2 content in flue gases when firing different fuels



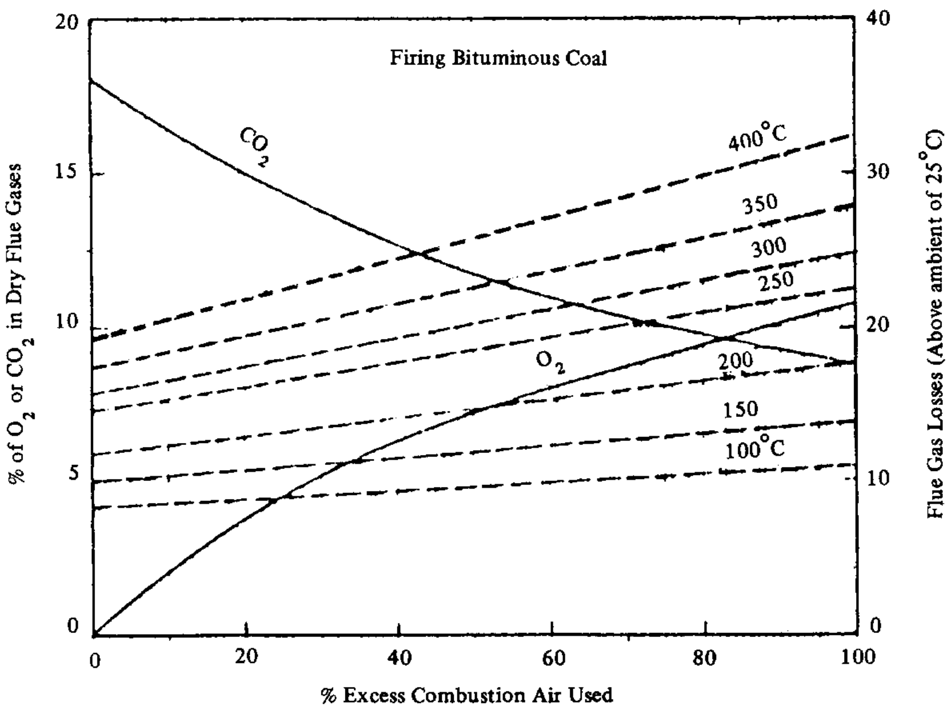


Figure 2. Flue Gas Heat Losses

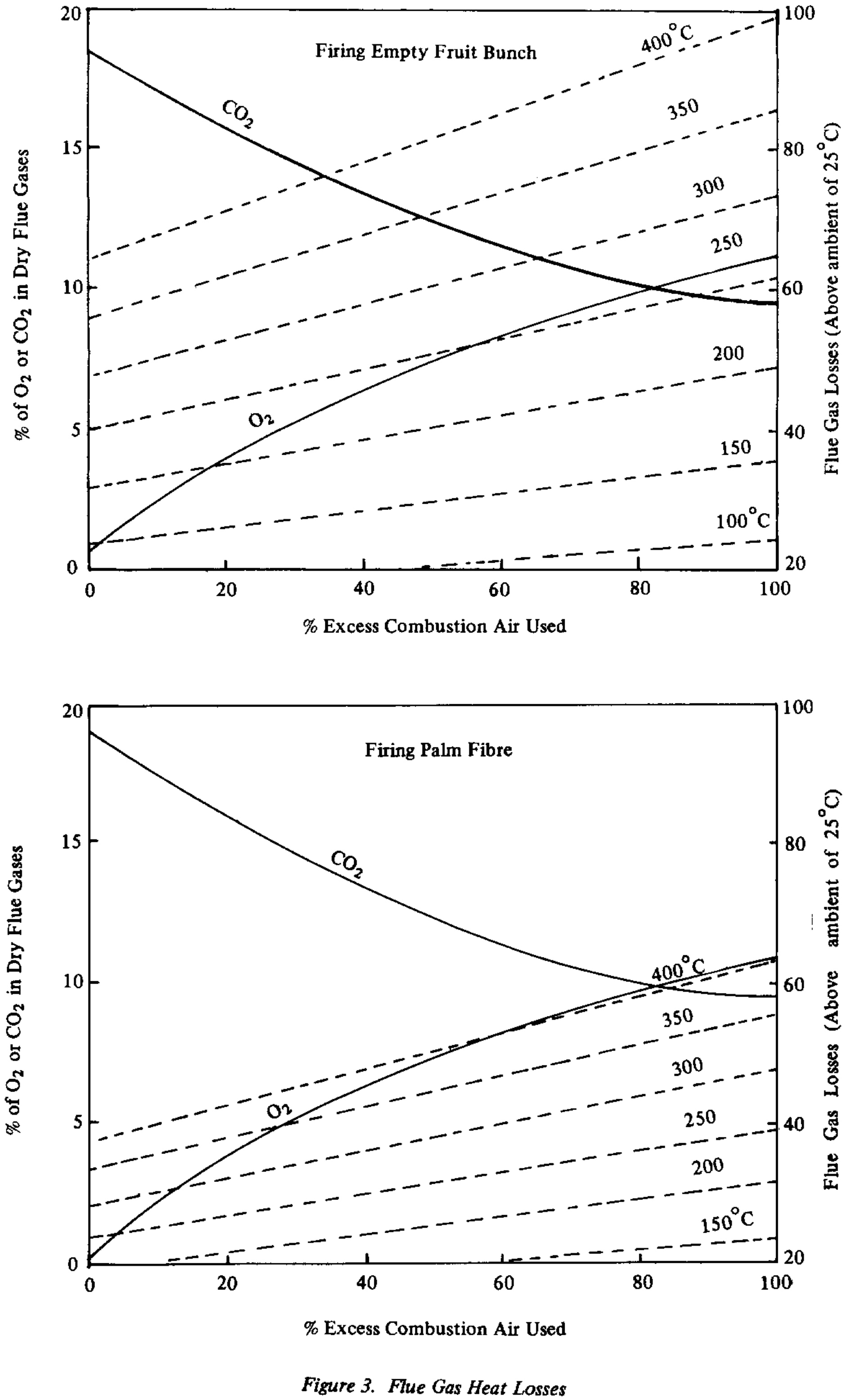
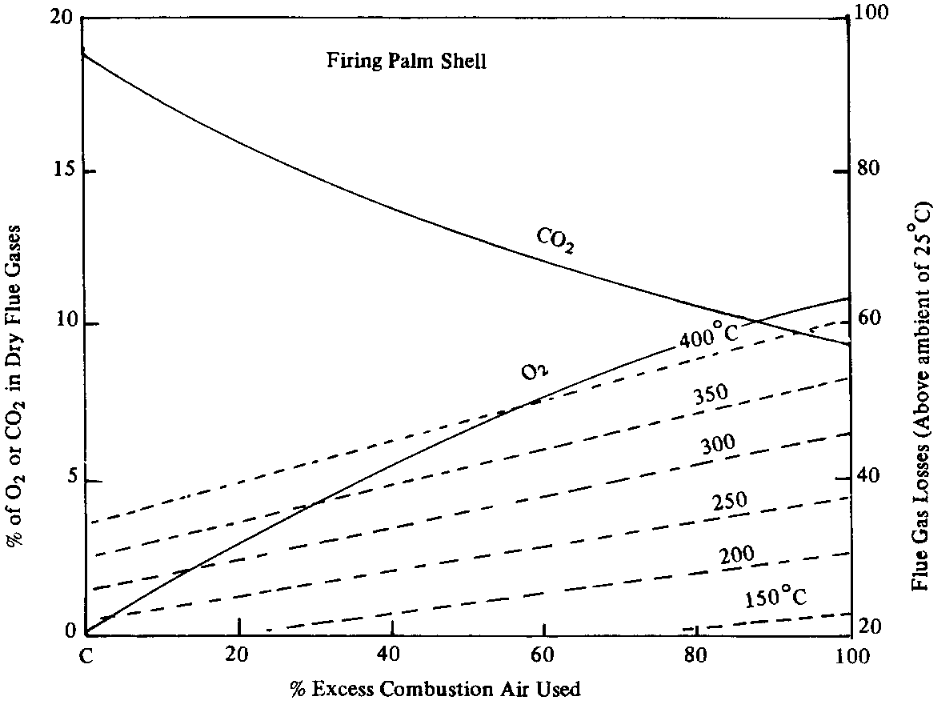
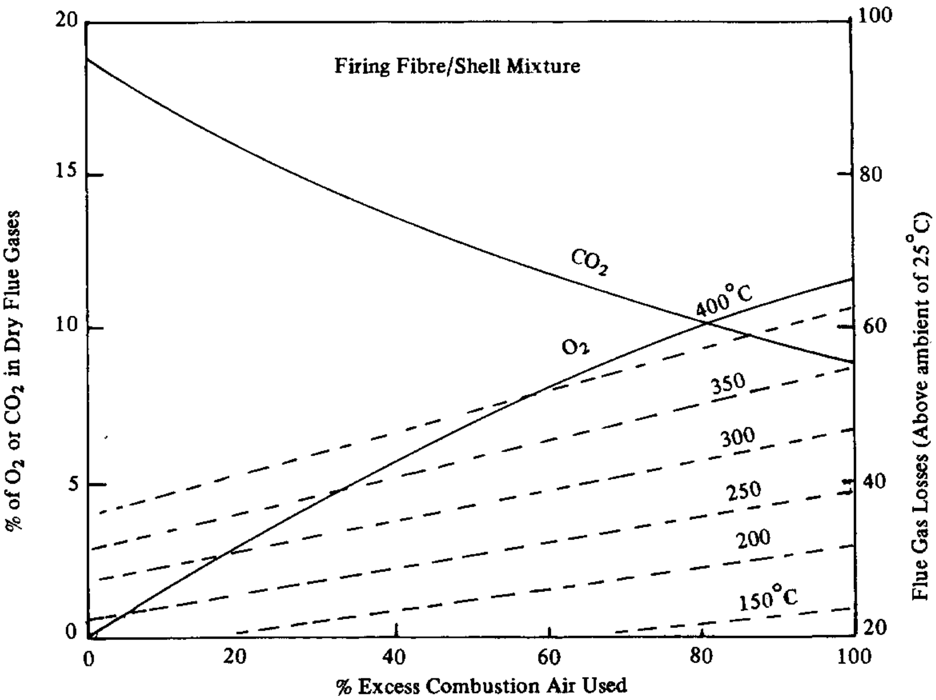


Figure 3. Flue Gas Heat Losses





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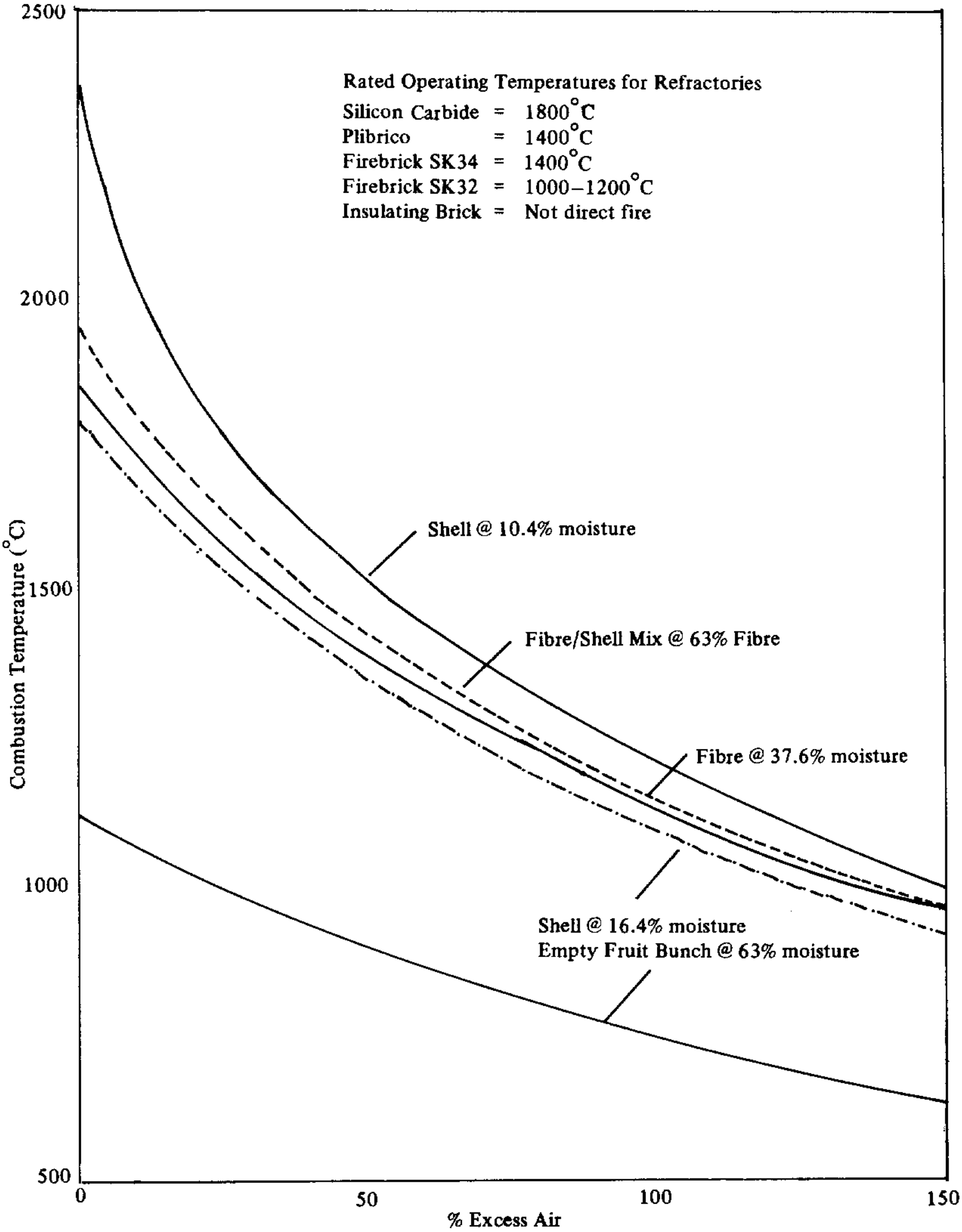

Figure 5. Estimated Combustion Temperatures When Firing Different Palm Waste Fuels

content in the exit gases is determined. Find the percentage of CO_2 (or O_2) on the left-hand scale and move horizontally to the CO_2 (or O_2) curve. From the point of intersection, move vertically up or down to the temperature curve, interpolating as necessary for the actual measured stack temperature. Finally, move from this second point of intersection horizontally to the right-hand scale and read off the percentage flue gas heat loss. For example, if 12.5% CO_2 is detected when burning the fibre/shell fuel in *Figure 4*, the flue heat loss is about 37% when the exit temperature is 300°C. If the exit temperature is higher by 50°C, the flue losses increases to 43%. At both conditions, the percentage excess air used is 50%. For the same conditions, flue losses for the high moisture EFB can be shown to be around 60% and 70% respectively. Clearly, if palm waste fuels are to be efficiently used, they must be kept as dry as possible. Proper storage designs should be considered especially in the context of boiler automation. EFB certainly need a certain degree of dewatering first, else the combustion energy will simply go to waste, not mentioning other difficulties that may arise.

Furnace or Combustion Temperatures

Figure 5 shows the estimated combustion temperatures for different typical fuel conditions as a function of percentage excess air used. The variation is a sensitive one and increasing excess air not only increases the flue gas heat losses but also considerably reduces attainable combustion temperatures. At 30% excess air using a typical fibre/shell fuel mix, the combustion temperature is about 1600°C. This figure drops to 1450°C if the excess air is increased by a further 30%.

Another interesting indication is the behaviour of equally wet fibre and shell. Apparently, although shell has a higher GCV (or NCV for a given moisture content), it leads to slightly lower furnace temperatures compared to those attainable by correspondingly wet fibres. This is due to the offset by the higher total heat capacities of the gaseous products arising from higher C composition of the shell and combustion air requirements.

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