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Biomass combustion systems. A guide for monitoring and efficient operation

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Natural Resources Institute

Biomass Combustion Systems

A Guide for Monitoring and Efficient Operation

In developing countries a large number of processing industries rely on biomass fuels for their operation. These fuels are, in the main, derived from forest resources. Agricultural residues such as rice husks also play an important role. The processing industries tend to be concentrated in particular areas and their impact on local forest resources and markets for biomass fuels can be considerable. It is essential that these valuable resources are used with optimum efficiency to minimize environmental impact. The efficient use of biomass resources for fuel requires an understanding of the basic principles underlying: combustion process; design of combustion equipment; and monitoring of equipment used for the generation of heat. This publication addresses these topics from a practical perspective. The essential theoretical background is presented but is kept to a minimum.

Biomass Combustion Systems: A Guide for Monitoring and Efficient Operation is the second in a series of publications and will be of interest to plant operators and researchers in the field of biomass combustion; and students of engineering. It is part of a continuing effort by the Natural Resources Institute to improve efficiency of utilization of fuelwood; and where possible to encourage replacement of fuelwood with agricultural and forestry residues such as rice husks and sawdust.

Biomass Combustion Systems

A Guide for Monitoring and Efficient Operation

A.S. Tariq, P. Reupke and G. Sarwar

NRI
Natural Resources Institute

The scientific arm of the
Overseas Development Administration

The Natural Resources Institute (NRI) is an internationally recognized centre of expertise on the natural resources sector in developing countries. It forms an integral part of the British Government's overseas aid programme. Its principal aim is to alleviate poverty and hardship in developing countries by increasing the productivity of their renewable natural resources. NRI's main fields of expertise are resource assessment and farming systems, integrated pest management, food science and crop utilization.

NRI carries out research and surveys; develops pilot-scale plant, machinery and processes; identifies, prepares, manages and executes projects; provides advice and training; and publishes scientific and development material.

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NOTES

1. Unless otherwise stated, moisture contents are expressed on a wet basis.

2. The term woody biomass is used to describe fuelwood, scrubwood, brushwood and wastes from forestry and wood working industries.

3. While the basic principles described in this publication can be applied to a wide variety of fuels, issues specific to fuels other than woody biomass and agricultural residues are not covered.

NOMENCLATURE

A — surface area (m^2)

A_e — excess air (percentage of stoichiometric air)

AFR — air to fuel ratio (kg air/kg fuel)

A_s — stoichiometric air (kg of air/kg of fuel)

C_a — ash content on a wet basis (percentage by mass)

C_{ad} — ash content on a dry basis (percentage by mass)

C_C — carbon content on a dry ash free basis (percentage by mass)

C_{fd} — fixed carbon content on a dry basis (percentage by mass)

C_H — hydrogen content on a dry ash free basis (percentage by mass)

C_m — moisture content on a wet basis (percentage by mass)

C_{md} — moisture content on a dry basis (percentage by mass)

C_N — nitrogen content on a dry ash free basis (percentage by mass)
C_O — oxygen content on a dry ash free basis (percentage by mass)
C_p^* — effective heat capacity of the combustion products (kJ/kg °C)
C_S — sulphur content on a dry ash free basis (percentage by mass)
C_{vd} — volatile matter content on a dry basis (percentage by mass)
d_t — thermocouple diameter (m)
E — efficiency as a percentage of the heat input into the combustion system
E_h — rate of heat extraction (expressed on the basis of one kg of fuel)
FT — flow temperature (°C)
f_{H_2O} — mass fraction of the water vapour in the combustion products defined in equation 26
GCV — gross calorific value (kJ/kg or MJ/kg)
Gr_f — Grashoff number at film temperature (dimensionless)
g — acceleration due to gravity (9.81 m/s^2)
HHC — higher heat content (kJ/kg or MJ/kg)
HHV — higher heating value (kJ/kg or MJ/kg)
HT — hemispherical temperature (°C)
h — heat transfer coefficient (kW/m^2 °C)
h_c — convective heat transfer coefficient (kW/m^2 °C)
IDT — initial deformation temperature (°C)
k_f — thermal conductivity of air at film temperature (kW/m °C)
k_g — thermal conductivity of gas (kW/m °C)
L — characteristic dimension in equations 53 and 55 (m)
L_1 — loss due to the sensible heat in the dry flue gas (as percentage of gross heat input into the system)
L_2 — loss due to the water formed from combustion of hydrogen in the fuel (as percentage of gross heat input into the system)
L_3 — loss due to the moisture contained in the fuel (as percentage of gross heat input into the system)
L_4 — loss due to the incomplete combustion of fuel resulting in carbon monoxide in the flue gas (as percentage of gross heat input into the system)
L_5 — loss due to the unburnt carbon in ash and grit (as percentage of gross heat input into the system)
L_6 — loss due to the elevated temperature of ash when discharged from the combustion equipment (as percentage of gross heat input into the system)
L_7 — loss due to the heat convected and radiated from the outer fabric of the combustion equipment (as percentage of gross heat input into the system)
LHC — lower heat content (kJ/kg or MJ/kg)
LHV — lower heating value (kJ/kg or MJ/kg)
M_C — relative molar mass of carbon
M_{CO_2} — relative molar mass of carbon dioxide
M_H — relative molar mass of hydrogen
M_{N_2} — relative molar mass of nitrogen

M_{O_2} — relative molar mass of oxygen

m_t — mass of the gaseous combustion products (excluding ash) per unit mass of fuel

NCV — net calorific value (kJ/kg or MJ/kg)

Nu — Nusselt number (dimensionless)

n_{CO_2} — number of kmol of carbon dioxide formed from combustion of carbon in one kg of fuel

n_{H_2O} — number of kmol of water formed from combustion of hydrogen in one kg of fuel

n_{N_2} — number of kmol of nitrogen supplied with the combustion air per kg of fuel

n_{O_2} — number of kmol of oxygen which appear in the dry flue gas per kg of fuel

n_t — total number of kmol of dry flue gas per kg of fuel

Pr_f — Prandtl number for air at film temperature (dimensionless)

Q_c — convected heat loss (kW)

Q_{gr} — heat radiated from gas to thermocouple (kW)

Q_k — heat conducted along thermocouple stem (kW)

Q_r — radiated heat loss (kW)

Q_t — total heat loss (kW)

Ra_f — Raleigh number at film temperature (dimensionless)

Re — Reynolds number (dimensionless)

R_{fu} — fuel usage rate (kg/s)

ST — softening temperature (°C)

T_a — ambient temperature (K)

T_g — true gas temperature (K)

T_s — surface temperature (K)

T_t — temperature indicated by thermocouple (K)

T_w — wall temperature (K)

t — temperature (°C)

t_a — ambient temperature (°C)

t_a — reference temperature (°C)

t_{ad} — adiabatic flame temperature (K or °C)

t_f — film temperature = $(t_s + t_a)/2$

t_g — temperature of the flue gas leaving the combustion system (°C)

t_r — temperature of the ash leaving the combustion system (°C)

t_s — surface temperature (°C)

U_c — unburnt carbon in ash (as percentage of the mass of the ash collected)

u_g — gas velocity (m/s)

V_{CO_2} — concentration of CO_2 in dry flue gas (as percentage volume)

$V_{CO_2,s}$ — concentration of CO_2 in dry flue gas calculated for stoichiometric fuel and air mixture (as percentage volume)

V_{N_2} — concentration of nitrogen in dry flue gas (as percentage volume)

V_{O_2} — concentration of oxygen in the dry flue gas (as percentage volume)

w_d — mass of dry flue gas per unit mass of the fuel burnt

α_C — carbon content (as percentage of the mass of the fuel as burnt)

α_H — hydrogen content (as percentage of the mass of the fuel as burnt)

α_O — oxygen content (as percentage of the mass of the fuel as burnt)

β_f — coefficient of cubical expansion for air at film temperature (1/K)

ε_s — emmissivity of the surface

ε_t — emmissivity of thermocouple

μ_f — viscosity of air at film temperature (N s/m^2)

μ_g — dynamic viscosity of gas (N s/m^2)

ρ_f — density of air at film temperature (kg/m^3)

ρ_g — density of gas (kg/m^3)

σ — Stefan-Boltzmann constant (5.67×10^{-11} kW/m^2 K^4)

SUMMARY

In developing countries, biomass represents the main source of energy with 300 to 375 million tonnes being used in small- to medium-scale industries. This industrial use causes local wood supply and associated deforestation problems which can be alleviated by efficient use of the fuel. This publication, which forms part of a series, is intended for use by plant operators and researchers in the field of biomass combustion to enable the evaluation of plant performance and provide the means to improve it.

Combustion calculations including stoichiometric air requirements, theoretical flue gas composition and adiabatic flame temperatures are explained in detail. Fuel properties of over 140 biomass materials are tabulated.

A wide range of equipment is available for biomass combustion, some of which is derived from systems designed for solid fossil fuel combustion. Some of the considerations required to adapt such equipment are covered and a brief review of the different types of solid fuel combustion systems is included.

Procedures and instrumentation for measurement of gas composition and temperatures in combustion equipment are reviewed and the advantages and disadvantages of each type of instrument are discussed. Methods for correcting systematic errors in gas temperature measurement are explained. The results of the measurements can be used to calculate the efficiency of the combustion system and the magnitude of the different losses.

RESUME

Dans les pays en voie de développement, la biomasse représente la principale source d'énergie, de 300 à 375 millions de tonnes étant mises en oeuvre dans les industries de petite à moyenne échelle. Cet emploi industriel provoque des problèmes locaux d'approvisionnements en bois et le déboisement connexe qui peuvent être soulagés avec l'utilisation efficace du combustible. Cette publication, faisant partie d'un ensemble, est destinée aux exploitants d'installations et aux chercheurs dans le domaine de la combustion des biomasses pour permettre l'évaluation des performances des installations et elle compris de moyens de les améliorer.

Les calculs de combustion, y compris les exigences stoechiométriques de l'air, la composition théorique des gaz de carneau ainsi que les températures adiabatiques de flamme sont expliqués en détail. Les propriétés combustibles de plus de 140 matériaux de biomasse sont presentés sous forme de tableaux.

Une gamme importante d'équipements est disponible pour la combustion des biomasses; certains d'entre eux étant dérivés de systèmes étudiés pour la combustion de combustibles fossiles solides. Cette publication traite certaines considérations exigées pour l'adaptation de tels équipements et il est brièvement passé en revue les différents types de systèmes de combustion des combustibles solides.

Les modalités et les appareillages de mesure de la composition et des températures des gaz dans les équipements de combustion sont passés en revue et on discute les avantages et les inconvénients de chaque type d'appareillages. Il est expliqué les méthodes de correction des erreurs systématiques dans les mesures des températures des gaz. Les résultats des mesures peuvent être employés pour calculer le rendement du système de combustion ainsi que l'importance des diverses pertes.

RESUMEN

Con un total de entre 300 y 375 millones de toneladas utilizadas por la pequeña y mediana industria, la biomasa es la principal fuente de energía en los países en desarrollo. El empleo industrial de la biomasa resulta en problemas de despoblación forestal y de suministro local de leña, que podrían ser aliviados mediante un uso eficiente del combustible. Esta publicación, que forma parte de una serie, ha sido pensada para operadores de planta e investigadores en combustión de la biomasa, con vistas a la evaluación del rendimiento de la planta y establecimiento de métodos que permitan mejorarlo.

La publicación presenta de manera detallada cálculos de combustión, incluyendo requisitos estequiométricos de aire, composición teórica de la composición de los gases de la combustión y temperaturas adiabáticas de la llama. También se tabulan las propiedades de combustible de más de 140 materiales de biomasa.

Se dispone de una amplia gama de equipo para la combustión de la biomasa, derivado, en parte, de sistemas diseñados para la combustión de combustibles fósiles sólidos. En una breve revisión de los distintos tipos de sistemas de combustión de combustibles sólidos se presentan algunas consideraciones requeridas para adaptar dicho equipo.

También se examinan en esta publicación los procedimientos e instrumental para la medición de la composición de los gases y las temperaturas de los equipos de combustión, examinándose las ventajas y desventajas de cada tipo de instrumento. Se ofrece asimismo una explicación de los métodos de corrección de errores sistemáticos en la medición de la temperatura de los gases. Los resultados de las mediciones podrán ser utilizados para el cálculo de la eficiencia del sistema de combustión y la magnitud de las distintas pérdidas posibles.

INTRODUCTION

In developing countries biomass represents the main source of energy. Estimates suggest that 1500 million tonnes of fuelwood are used annually (FAO, 1990). The major proportion of this consumption is for domestic use. However, between 20% and 25% of fuelwood is used in small- to medium-scale industries (Breag *et al.*, 1986; Barnard, 1987; Vaclav, 1983). The importance of fuelwood in industrial energy supply varies considerably between countries. In Table 1 examples are given of the contributions of fuelwood to national industrial energy demand in various countries.

Table 1 Examples of contributions of fuelwood to national industrial energy demand in some developing countries

Country	% of industrial energy demand met by fuelwood	Reference
Tanzania	88	1
Mozambique	69	1
Kenya	64	1
Sri Lanka	57	2
Brazil	21	2
India	6	2

References 1 O'Keefe *et al.*, 1984
2 Leach *et al.*, 1983

Although industrial demand for fuelwood is generally less than one-third of total consumption, its local impact is much greater than this figure suggests. The industrial and commercial users of fuelwood tend to be concentrated in particular locations. These concentrations of large users and the resulting cash incentives to suppliers of fuelwood distort local fuelwood demand and exacerbate pressures on the local forest resources, resulting in over-exploitation (Barnard, 1987). Furthermore, industrial applications normally require good-sized logs as opposed to the branches and brushwood which supply the bulk of fuel for rural domestic use. This requirement causes whole trees to be cut down to meet industrial and urban demand for fuelwood instead of trimmings and dead branches which supply energy for the rural areas. In view of this propensity for industrial users of fuelwood to distort local markets and to create excessive pressure on forest resources, it is imperative that this fuel be used with optimum efficiency.

Efficient use of biomass fuels requires a basic understanding of the combustion principles, means of measuring and methods for evaluating thermal efficiencies of combustion/heat exchanger and boiler systems. The Natural Resources Institute (NRI) has been actively promoting better use of biomass for industrial applications and, where possible, to substitute fuelwood with processing residues such as sawdust and rice husks (Breag *et al.*, 1986; 1992; Robinson, 1991; Robinson and Breag, 1992; Robinson *et al.*, 1993; Rogers *et al.*, 1991; Sarwar *et al.*, 1992; Tariq and Lipscombe, 1992; Williams and Robinson, 1993).

This publication is the second in a planned series of publications being prepared for researchers and workers engaged in biomass combustion and students of engineering. It explains the fundamentals of combustion of biomass fuels, equipment needed for measurements, and methods to evaluate thermal efficiency. The title of the first publication in this series is: *Biomass Combustion Systems – Flue Gas Losses and Equipment Efficiency* (Breag et al., 1992).

PROPERTIES OF BIOMASS FUELS

Biomass fuels are solid carbonaceous materials derived from living plant matter. These fuels include: wood; forestry wastes from industries such as sawmills and plywood factories; and agricultural residues such as straw, rice husks and sugar-cane bagasse.

There are many properties of these fuels which must be considered for particular applications. These include:

- bulk density
- moisture content
- proximate analysis
- ultimate analysis
- gross and net calorific value
- ash properties
- size

Bulk density

Bulk density is defined as the mass of a loosely packed specified volume of biomass material. Bulk density can be determined by a number of standard procedures (ASTM E873–82, 1982; ASAE S269.3, 1985) and is affected by moisture content, shape and form of the material. Knowledge of the bulk density is important in determining requirements for and costs of transport and storage, and the design of handling and conveying systems. Bulk density is also an important factor to be taken into account in the design of combustion chambers and furnaces. In Table A1 in the Appendix comparative values of the bulk density of biomass materials are listed.

Moisture content

The moisture content of biomass fuels is one of its most important properties. Free moisture in the fuel influences performance and costs at all stages.

During transportation, the free moisture is an additional weight which has to be carried. Water as free moisture in biomass fuels has no heating value and therefore reduces the amount of heat available from a given quantity of fuel. During combustion, the free moisture in the biomass fuels absorbs heat by evaporation of the liquid water and heating of the resulting water vapour. This lowers the amount of useful heat available from the fuel and also results in decreased combustion temperatures. The effect of the moisture on the useful heat available from fuelwood is shown in Figure 1. For example, at 60% moisture content, the mass of wet fuelwood required is three times the mass of dry fuelwood for the same amount of useful heat. This is before the effect of the moisture content on combustion temperatures and losses in the form of heated water vapour in the flue gases are considered. Therefore for efficient use of biomass fuels the moisture content should be reduced to as low a value as is practicable. This quite often means provision of adequate storage space where biomass fuels can be left for a considerable length of time for air drying. The moisture content of the green wood can be reduced to 25—30% by air drying for four to six months (Pratt, 1986) and to a fairly constant value of 20% in twelve months (Klar and Rule, 1925). In Table 2, loss of moisture as a function of time after felling for a selected species of trees (Klar and Rule, 1925) is illustrated. The drying times depend very much on the size of the wood, weather conditions and the method of storage.

The moisture content must be taken into account in the design of the combustion equipment to ensure that combustion chamber temperatures are maintained within limits at which good combustion can take place without causing ash fusion and fouling. In Table 3 the effect of moisture content on the design of biomass fired boilers is shown.

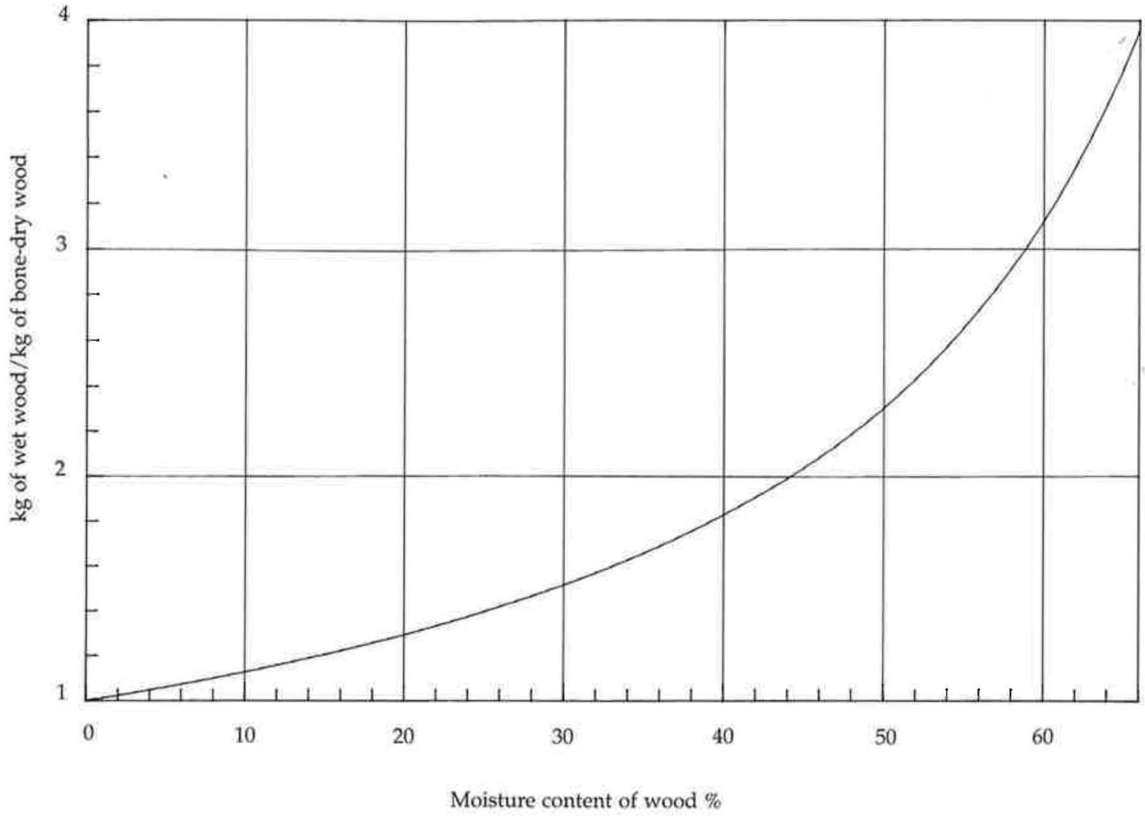

Figure 1 Relative mass of wet wood required to supply useful energy equivalent to that contained in bone-dry wood

The moisture content of biomass fuels is determined by heating a representative sample, at 105 °C in a ventilated oven, until constant mass is reached (TAPPI Standard T 18 m-50; TRADA, 1985). The mass lost during heating is then the mass of water evaporated as free moisture from the sample. Two definitions of the moisture content of biomass fuels, on a wet or a dry basis, are used in the literature.

Percentage moisture content on a wet basis C_m is defined as:

$$C_m = \frac{\text{mass of water in the fuel}}{\text{mass of wet fuel}} \times 100 \tag{1}$$

Percentage moisture content on a dry basis C_{md} is defined as:

$$C_{md} = \frac{\text{mass of water in the fuel}}{\text{mass of dry fuel}} \times 100 \tag{2}$$

Percentage moisture contents on a wet and dry basis are related by the following expressions:

$$C_{md} = \frac{100 \times C_m}{(100 - C_m)} \tag{3}$$

$$C_m = \frac{100 \times C_{md}}{(100 + C_{md})} \tag{4}$$

Table 2 Variation in moisture content of wood with time (Klar and Rule, 1925)

Kind of wood	Months after felling			
	6	12	18	24
Beech				
Trunkwood	23.2	19.3	17.4	17.7
Stout branchwood	33.5	24.0	19.8	20.3
Small branchwood	30.4	23.5	18.6	20.0
Oak				
Trunkwood	29.6	23.8	20.7	19.2
Stout branchwood	31.2	26.9	24.6	21.1
Small branchwood	32.7	26.7	23.4	20.3
Hornbeam				
Trunkwood	24.1	20.2	18.8	17.9
Stout branchwood	31.4	25.9	22.3	19.3
Small branchwood	27.2	23.1	20.6	18.6
Birch				
Trunkwood	23.3	18.1	16.0	17.2
Stout branchwood	37.3	29.0	24.1	21.8
Small branchwood	39.7	29.0	22.7	19.5
Silver fir				
Trunkwood	28.6	16.7	14.8	17.2
Stout branchwood	28.3	17.4	15.1	18.7
Small branchwood	33.8	16.9	15.2	18.1
Spruce				
Trunkwood	29.3	28.5	15.8	17.8
Stout branchwood	35.3	17.6	15.7	17.4
Small branchwood	41.5	18.7	15.6	17.4

In this publication the moisture content values are on a wet basis. Moisture content of the freshly harvested biomass fuels depends on the type of material, method of harvesting and weather at the time of harvesting. The moisture content of the freshly harvested wood can be of the order of 65%. Some typical values of moisture content for green biomass materials are given in Table A2 in the Appendix.

Proximate analysis

Proximate analysis is used to determine the percentages of volatile matter, fixed carbon and ash in a fuel. The results give an indication of the flaming and glowing combustion resulting from the gas phase combustion of volatile matter and combustion of the solid char (Rossi, 1984). The ash content provides a measure of the incombustible mineral matter in the fuel. The volatile matter and fixed carbon, and to a lesser degree the ash content, depend upon the conditions of measurement. As yet no universally accepted test standards specific to biomass materials exist, and reliance is generally made on standards developed for coal (ASTM 3172–73, 1984; BS 1016:Part 3, 1973). The volatile matter is determined by heating a sample at 900 °C for seven minutes in a closed crucible of a specified design. The loss of mass, after adjustment for free moisture, is treated as the volatile matter. The mass remaining in the crucible, minus the mass of ash, is termed fixed carbon.

The ash content is determined by incineration at 815 °C, in air, of a sample of biomass material. The sample is heated, in stages, for a specified period of time according to the standard test procedures (BS 1016:Part 3, 1973). The mass remaining after incineration is treated as ash. Alternative views on the correct temperature for the ash test have been put forward. For example, a temperature of 550 °C is recommended in the Swedish national standards for biofuels and is also the temperature recommended for the determination of the ash content for straw (IEA, 1992). However, a temperature of 815 °C corresponds more closely with conditions in combustion systems.

Table 3 The effect of moisture content on combustion chamber design for boilers fired with fibrous fuels (Magasiner and de Kock; 1987)

Moisture content range	Preferred combustion chamber and heat recovery combination	Comments
Greater than 56%	Refractory lined	Combustion unstable. Predrying required. This can be done either internally as in a hearth furnace or by means of an externally located predrying system.
50% to 56%	Partly water cooled with air pre-heater. Undergrate air temperature of at least 200°C required at 56% moisture content	Combustion relatively stable. Some refractory required in furnace to improve combustion stability.
40% to 50%	Partly water cooled with air pre-heater or economizer OR Fully water cooled with air pre-heater	Combustion stable. Unlikely for slag to form in partly water-cooled furnace. In fully water-cooled furnace an air pre-heater is advisable to improve combustion stability.
30% to 40%	Fully water cooled with economizer	Combustion stable with tendency for slag to form.
Less than 30%	Fully water cooled with economizer	Combustion stable. Strong tendency for slag to form, particularly with fuels having high alkali metal content.

All of these quantities are defined as a percentage of the mass of the sample. In literature, results are quoted on either a wet or a dry basis. Because of the wide variability of the moisture content, it is preferable to express results on the basis of the dry fuel for ease of comparison. The inherent ash in most biomass fuels is low, particularly in fuelwoods which usually have an inherent ash content of less than 1%. However, some biomass materials such as rice husks have a high ash content of the order of 20%. During harvesting, storage and handling, external mineral matter (soil) is quite often picked up, resulting in a higher ash content.

The volatile matter and fixed carbon in woody biomass materials fall in a narrow range of 75–85% and 15–25% respectively on a dry fuel basis. Table A3 in the Appendix is a compilation of the proximate analysis of biomass fuels quoted in the literature referenced. Where necessary, the values quoted in the literature have been adjusted to a dry fuel basis. Formulae for conversion of properties to different basis are presented in Table A6 in the Appendix and a summary of symbols used in this publication for fuel properties and their basis is given in Table A7 in the Appendix.

Ultimate analysis

Ultimate analysis determines chemical composition of fuels in terms of carbon, hydrogen, oxygen, nitrogen and sulphur as mass percentages of dry and ash free (daf) biomass material. This basis for reporting of ultimate analysis and gross calorific value has the advantage of removing the effects of contamination of sample with soil and variability of the moisture content. Knowledge of the chemical composition of the fuel is essential for estimating air requirements and flue losses. It is also of importance in determining likely emissions of pollutants such as nitrogen oxides. The ultimate analysis is often determined according to the standards developed for coal (BS 1016:Part 6, 1977; ASTM D3176–84, 1984). Biomass materials show a remarkable uniformity in chemical composition. Nitrogen and sulphur are present only in small quantities. Woody biomass materials can be represented by the following average composition on a daf basis for routine calculations for combustion systems (Breag *et al.*,1986):

Carbon, C_C	50% by mass;
Hydrogen, C_H	6% by mass;
Oxygen, C_O	44% by mass.

Table A3 in the Appendix is a compilation of the ultimate analysis of biomass materials quoted in the literature. Where necessary the values have been adjusted to a daf basis.

Calorific values

The calorific value of a fuel is an important property and it determines the quantity of fuel which must be burnt to meet a given duty. The calorific values of biomass fuels are measured according to the standards developed for coal (BS 1016:Part 5, 1977; ASTM D2015–85, 1985). A known quantity of fuel is burnt in an atmosphere of oxygen in a bomb calorimeter. Prior to use, the bomb calorimeter is standardized against the heat released from the combustion of a sample of benzoic acid of thermochemical standards quality. The test is carried out at temperatures close to 25 °C and the water formed during combustion remains in liquid form. The heat released during the combustion reaction under these conditions, after correction for formation of acids and deviation of test temperature from 25 °C, is termed gross calorific value (GCV). The adiabatic bomb calorimeter is the most commonly used form of instrument for this purpose. The gross calorific values of most biomass materials fall in a narrow range when calculated on a daf basis. For woody biomass an average value of 19 900 kJ/kg on a daf basis has been derived from 338 values quoted in the literature and this value can be used for most routine calculations (Breag *et al.*, 1986; Harker *et al.*, 1982).

Under operational conditions, the water contained in the fuel as moisture and the water formed from the conversion of hydrogen, remain in vapour form and the heat of vaporization of water included in the gross calorific value is not usefully extracted. The net calorific value of a fuel (NCV) is a measure of the useful heat which will be liberated during complete combustion of the fuel, and is defined as the heat released during combustion of a fuel when water formed during combustion remains in the vapour state and the temperature of the products of combustion is 25 °C. The net calorific values of a fuel on an 'as-fired' basis (that is, taking account of moisture and incombustible mineral matter as ash) can be derived from the hydrogen, moisture and ash contents of the fuel and the latent heat of vaporization of water at 25 °C, as given below:

$$\mathrm{NCV} = \mathrm{GCV}\left(1 - \frac{C_m}{100} - \frac{C_a}{100}\right) - 2442\left\{\frac{C_m}{100} + \frac{C_H \times 9}{100}\left(1 - \frac{C_m}{100} - \frac{C_a}{100}\right)\right\} \qquad \textbf{(5)}$$

Where hydrogen content, C_H, and gross calorific value, GCV, are on the basis of daf fuel. The moisture content, C_m, and ash content, C_a, are on a wet basis.

For routine calculations taking hydrogen content as 6% and GCV as 19 900 kJ/kg on a daf basis, the above equation reduces to:

$$\mathrm{NCV} = 18581.3 - 210.2 \times C_m - 185.8 \times C_a \quad \mathrm{kJ/kg} \qquad \textbf{(6)}$$

The gross calorific values of biomass fuels can also be calculated from the knowledge of the elemental composition of the biomass material with the use of various empirical correlations given in the literature. A selection of these formulae is given in Table 4, together with the GCV calculated for woody biomass fuel of composition: 6% hydrogen (C_H); 50% carbon (C_C); and 44% oxygen (C_O). Nitrogen (C_N) and sulphur (C_S) are considered to be negligible. The calculation of gross calorific values from elemental analyses is a good check for the reliability of a material's composition and calorific value measurements in most cases (Buckley, 1991).

Other terminology used for gross calorific value are higher heat content (HHC) and higher heating value (HHV). Similarly, net calorific value is also referred to as the lower heat content (LHC) and lower heating value (LHV) of the fuel. Table A3 in the Appendix lists gross calorific values of biomass fuels abstracted from literature. Where necessary, values have been adjusted to a daf basis.

Table 4 Empirical formulae for calculating gross calorific values from ultimate analysis of fuels

Formula	Calculated GCV kJ/kg	Reference
$GCV = 436C_C - 1662$	20 140	1
$GCV = 336C_C + 1418C_H - (153 - 0.72C_O)C_O + 94.1C_S$	19 970	2
$GCV = 341.7C_C + 1322.1C_H - 119.8(C_O+C_N) + 123.2C_S$	19 750	3
$GCV = 328C_C + 1430C_H - 23.73C_N + 92.9C_S - (\frac{40109C_H}{C_C} + 346.6)$	19 820	4

References: 1 Tillman *et al.*, 1978.
2 Moat *et al.*, 1940.
3 Institute of Gas Technology, 1978.
4 Gore, 1982.

Notes: The carbon content C_C, hydrogen content C_H, oxygen content C_O, sulphur content C_S and nitrogen content C_N on a daf basis

Ash properties

The chemistry of ash plays an important role in its fouling, slagging, clinker formation and erosion properties. Ash fusion data provides information on the likely behaviour of the ash in the combustion chamber. Data on the fusion properties of ash are obtained by controlled heating of a standardized cone or a cylinder of an ash sample under reducing or oxidizing atmospheres (BS 1016: Part 15, 1970). Usually three temperatures are reported:

- the initial deformation temperature (IDT). This is the temperature at which the first rounding of the tip of the specimen occurs;
- hemispherical temperature (HT). This is the temperature at which the height of the specimen is half of the base and shape of the specimen is roughly hemi-spherical; and
- flow temperature (FT). This is the temperature at which the height of the ash specimen is a third of that for the hemispherical temperature.

ASTM standards (ASTM D1857, 1987) specify an additional temperature intermediate between IDT and HT. This is termed the softening temperature (ST) and is defined as the temperature at which the height of the specimen is equal to its width.

The British Standard recommends use of photographs to assist in the determination of these temperatures. Nowadays video cameras are also used.

Reducing atmospheres result in lower fusion temperatures and can therefore provide a guide for the temperatures at which ash fusion is unlikely to occur. Table A4 in the Appendix is a compilation of the fusion temperatures of ash from biomass materials, quoted in the literature. The difference between initial deformation and flow temperatures for wood ash is small (ETSU, 1990). In wood ash, alkali metal and phosphorus contents are high in comparison to coal ash. The alkali metals in wood ash are in a form which can be easily volatilized and deposited on heat transfer surfaces (ETSU, 1990). The levels of phosphate in coal ash, similar in magnitude to those in wood ash, are known to cause phosphate deposits in convective banks of water tube boilers (ETSU, 1990). The propensity of any fuel ash to fume and cause fouling is related to the alkali metal oxides to silica ratio and this ratio provides an illustration of the fouling potential of a fuel. The mechanisms for this are not clearly understood, but one explanation is that alkali metals which are not chemically bound to the silica, volatilize during combustion and recondense on cooler surfaces of the boilers and other equipment. Where gas temperatures are high, the recondensed materials can sinter and form hard deposits on the surfaces. Special care is needed in the design and operation of equipment if the alkali metal oxides to silica ratio in ash exceeds 2 (Magasiner *et al.*, 1987). The erosion of equipment surfaces is likely when this ratio is less than 0.3 (Magasiner *et al.*, 1987). Figure 2 is an illustration of the likely fouling and erosion potential of various biomass fuels. The foregoing illustrates the need to maintain a good control of combustion temperatures in expensive boiler equipment to avoid deterioration of performance caused by fouling and to reduce maintenance. A compilation of the chemical composition of ash from biomass materials is given in Table A5 in the Appendix.

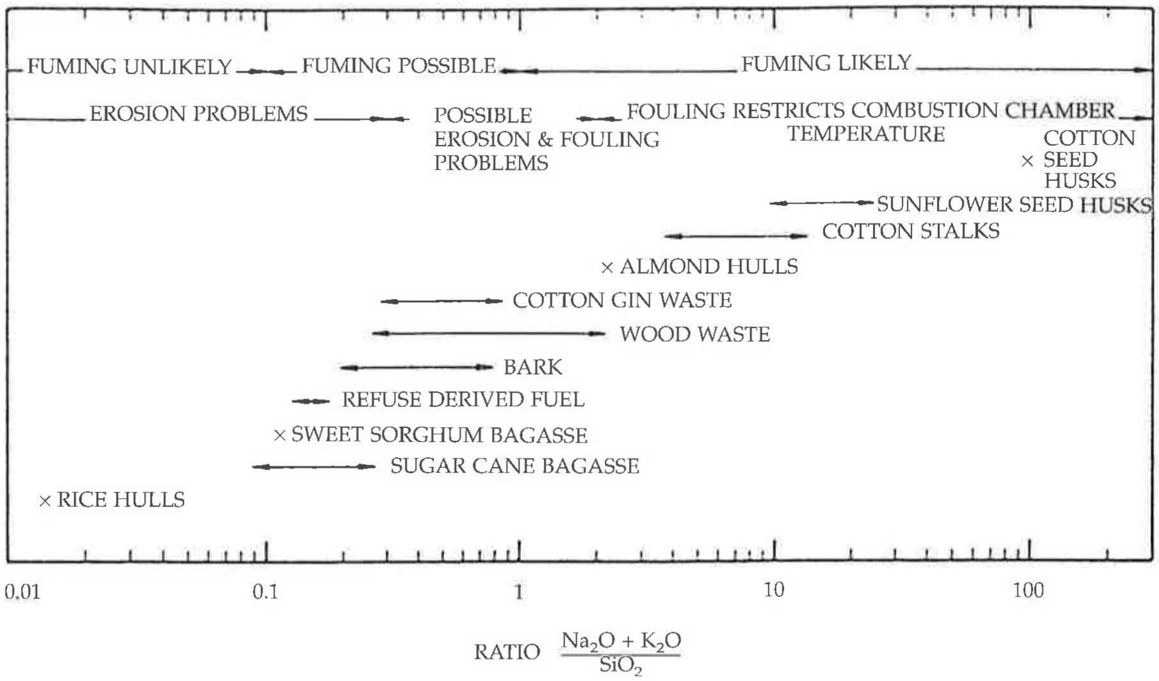

Figure 2 Fouling potential of ash from biomass material (Magasiner and de Kock, 1987)

Size

Fuelwood and many biomass fuels require size reduction and/or other preparation which is dependent upon the type and scale of the combustion equipment. Logs can only be satisfactorily used when firing manually. The equipment for manual firing is therefore limited to smaller scales and logs have to be prepared to a size which can easily be handled and evenly distributed in the combustion chamber. This type of equipment will generally be limited to stationary flat grates. With larger systems, mechanical feeding of fuel becomes essential and this in turn requires hogging or chipping of the fuel. The prepared fuel is transported to the combustion equipment by troughed conveyers, screws, belt conveyers, pneumatic conveyers or spreader stokers. The larger-scale combustion equipment for hogged or chipped fuel can incorporate various types of grates, including inclined grates, moving grates and under-feed stokers. The finely divided fuels such as sawdust, rice husks and chopped straw can be burnt on specially designed sloping grate systems or in suspension firing equipment. Control of the fuel preparation is important for efficient operation of larger systems. For example, equipment designed for chipped fuel will not function satisfactorily with larger chunks of fuelwood. These systems are described more fully in the section on *Equipment for biomass combustion*.

CALCULATIONS OF AIR REQUIREMENTS, THEORETICAL COMPOSITION OF FLUE GASES AND ADIABATIC FLAME TEMPERATURE

Introduction

The primary aim of a combustion system is to convert carbon (C) and hydrogen (H) contained in a fuel to carbon dioxide (CO_2) and water vapour (H_2O) respectively in the following reactions:

$$C + O_2 \rightarrow CO_2$$

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$$

The above equations represent the overall reactions in terms of starting materials and end products and are useful in deriving equipment efficiencies, theoretical flue gas composition and in determining requirements of combustion air. The actual reactions of any fuel with oxygen (O_2) proceed through a very large number of intermediate steps involving highly reactive radicals and atomic species in chain reactions. The practical calculations for a combustion system are based upon the end products of these reactions, that is, on CO_2 and H_2O. The oxygen required in the above reactions is supplied from air which contains approximately 79% (by volume) inert nitrogen. The energy released in the conversion of carbon and hydrogen not only heats the end products of combustion (CO_2 and H_2O) but also the nitrogen (N_2) and any excess oxygen. These gases carry heat out of the system via the flue.

In order to minimize the loss of heat, the quantity of air supplied to a combustion system should be the minimum required to achieve complete conversion of the fuel and to maintain combustion temperatures at the design limits of the equipment. The quantity of air supplied to a combustion system is conventionally expressed as a proportion of the air theoretically required to convert completely the carbon and hydrogen in the fuel to carbon dioxide and water vapour. This theoretical minimum amount of air is termed the stoichiometric quantity of air and is expressed as kg of air/kg of fuel. In practice all combustion systems, except specialized applications where reducing conditions are needed, require air in quantities greater than stoichiometric. The air supplied to a combustion system over the stoichiometric air requirements is called excess air and is expressed as a percentage of the stoichiometric quantity of air. Levels of excess air used are determined by the design of the equipment and should be maintained as low as possible within the specifications of the equipment.

Calculation of stoichiometric air

Stoichiometric air requirements can be calculated from knowledge of the ultimate analysis of fuel and that:

- each kilo mole (kmol) of carbon in fuel requires one kmol of oxygen for complete combustion;
- each kmol of hydrogen requires one-half of a kmol of oxygen for complete combustion;
- air contains approximately 21% by volume (or by kmol) oxygen and approximately 79% by volume (or by kmol) nitrogen; and
- air with the above composition has a molecular mass of 28.84 kg/kmol of air.

The stoichiometric air, A_s, is then given by:

$$A_s = \{(\frac{C_C}{M_C} + \frac{C_H}{2\,M_{H_2}} - \frac{C_O}{M_{O_2}})\,(1 + \frac{79}{21})\} \times (1 - \frac{C_m}{100} - \frac{C_a}{100})\,\frac{28.84}{100} \text{ kg of air/kg of fuel} \qquad \textbf{(7)}$$

where C_C, C_H, C_O are carbon, hydrogen and oxygen contents of the fuel on a dry ash free basis as percentage mass. C_m, C_a are moisture and ash contents of the fuel on a wet basis. M_C, M_H, M_{O_2} are molar masses of carbon, hydrogen and oxygen and have values of 12, 2 and 32 respectively. For woody biomass with a typical composition of 50% carbon, 6% hydrogen and 44% oxygen on a dry ash free basis, equation (7) reduces to:

$$A_s = 5.894\,(1 - \frac{C_m}{100} - \frac{C_a}{100}) \quad \text{kg of air/kg of fuel} \tag{8}$$

The air:fuel ratio, AFR, is defined as the mass of air supplied to a combustion system per unit mass of fuel as-fired, that is:

$$AFR = \frac{\text{air supplied kg/unit time}}{\text{fuel supplied kg/unit time}} \quad \text{kg air/kg fuel} \tag{9}$$

The excess air, A_e, is then defined as:

$$A_e = (\frac{AFR}{A_s} - 1)\,100 \tag{10}$$

Therefore 100% excess air is equal to twice the stoichiometric quantity of air.

Calculations of the theoretical composition of flue gases

The flue gases contain products of combustion comprising carbon dioxide, carbon monoxide (CO) (in the case of incomplete combustion), water vapour, nitrogen and any excess oxygen. Comparison of the theoretically calculated composition of the flue gas with that measured in the flue indicates whether the air:fuel ratio in the equipment is as intended. The flue gases are analysed on a dry basis, that is, water vapour formed during combustion is removed before analysis is carried out. The theoretical composition of the dry flue gases can be calculated from the composition of the fuel and air:fuel ratio (or excess air levels) by the following procedure which is based upon one kg of fuel.

The number of kmol of carbon dioxide, n_{CO_2}, formed from one kg of fuel on an as-fired basis can be calculated from:

$$n_{CO_2} = \frac{C_C}{12\times100}\,(1 - \frac{C_m}{100} - \frac{C_a}{100}) \tag{11}$$

The number of kmol of water, n_{H_2O}, formed from combustion of hydrogen in one kg of fuel is given by:

$$n_{H_2O} = \frac{C_H}{2\times100}\,(1 - \frac{C_m}{100} - \frac{C_a}{100}) \tag{12}$$

The number of kmol of oxygen, n_{O_2}, which appear in the dry flue gas is determined from oxygen contained in the fuel and air less that used for the formation of CO_2 and H_2O and is given by:

$$n_{O_2} = \frac{C_O}{32\times100}\,(1 - \frac{C_m}{100} - \frac{C_a}{100}) + 0.21\,\frac{AFR}{28.84} - \frac{n_{H_2O}}{2} - n_{CO_2} \tag{13}$$

The number of kmol of nitrogen, n_{N_2}, supplied with the combustion air is calculated from:

$$n_{N_2} = 0.79\,\frac{AFR}{28.84} \tag{14}$$

Therefore the total number of kmol, n_t, of dry flue gas per kg of fuel is given by:

$$n_t = n_{CO_2} + n_{O_2} + n_{N_2}$$

$$= \frac{1}{100}\,(\frac{C_O}{32} - \frac{C_H}{4})\,(1 - \frac{C_m}{100} - \frac{C_a}{100}) + \frac{AFR}{28.84} \tag{15}$$

According to Avogadro's hypothesis, kmol and volumes are numerically interchangeable parameters for gases under constant temperature and pressure conditions. The theoretical composition of flue gases as percentage volumes is therefore given by:

$$V_{CO_2} = \frac{n_{CO_2}}{n_t} 100 \qquad \textbf{(16)}$$

$$V_{O_2} = \frac{n_{O_2}}{n_t} 100 \qquad \textbf{(17)}$$

Where V_{CO_2} and V_{O_2} are volume percentages of carbon dioxide and oxygen in the dry flue gas.

If the measured composition of the dry flue gas is significantly different from that calculated from the equations above, it would indicate either that some of the carbon had remained unburnt, or that the air:fuel ratio is different from that used in deriving the theoretical flue gas composition. Equations (11)–(14) simplify to the following for typical woody biomass materials.

$$n_{CO_2} = 0.0417\ (1 - \frac{C_m}{100} - \frac{C_a}{100}) \qquad \textbf{(18)}$$

$$n_{O_2} = 0.0073\ AFR - 0.043\ (1 - \frac{C_m}{100} - \frac{C_a}{100}) \qquad \textbf{(19)}$$

$$n_{N_2} = 0.0274\ AFR \qquad \textbf{(20)}$$

$$n_t = 0.0347\ AFR - 0.0013\ (1 - \frac{C_m}{100} - \frac{C_a}{100}) \qquad \textbf{(21)}$$

Adiabatic flame temperatures

An estimate of the temperature in a combustion system can be obtained from knowledge of:

- the net calorific value of the fuel;
- the mass and enthalpy of combustion products;
- the heat extraction and fuel feed rates; and
- the air:fuel ratio.

A special case is when no heat is lost from the fuel and air mixture during the combustion process. The temperature reached in such an adiabatic system is the maximum possible for a given fuel/air mixture and is called the 'adiabatic flame temperature'. At high excess air levels, calculation of the adiabatic flame temperature is simple and straightforward but at low excess air levels, temperatures reached are high and combustion products contain significant concentrations of dissociated chemical species. The calculations of adiabatic flame temperatures in these cases require that the compositions of combustion products are determined in accordance with principles of thermodynamic equilibria. Such calculations are tedious and involved, and can be performed on the basis of the minimization of Gibbs' free energy (Zeleznik and Gordon, 1968) or on the basis of equilibrium constants (Harker, 1967; Harker and Allen, 1969). For fuels containing carbon and hydrogen, burning in air, the important chemical species to be considered are CO, CO_2, H_2, H_2O, OH, H, O_2, O, NO and N_2 (Harker, 1967). Computer codes for such calculations exist (Reynolds, 1982; Harker, 1967; Harker and Allen, 1969; Tariq, 1981). A computer programme (Tariq, 1981) was used to calculate adiabatic flame temperatures of typical woody biomass material (ash-free) at a range of moisture contents and burning with a range of excess air levels. The results are plotted in Figure 3.

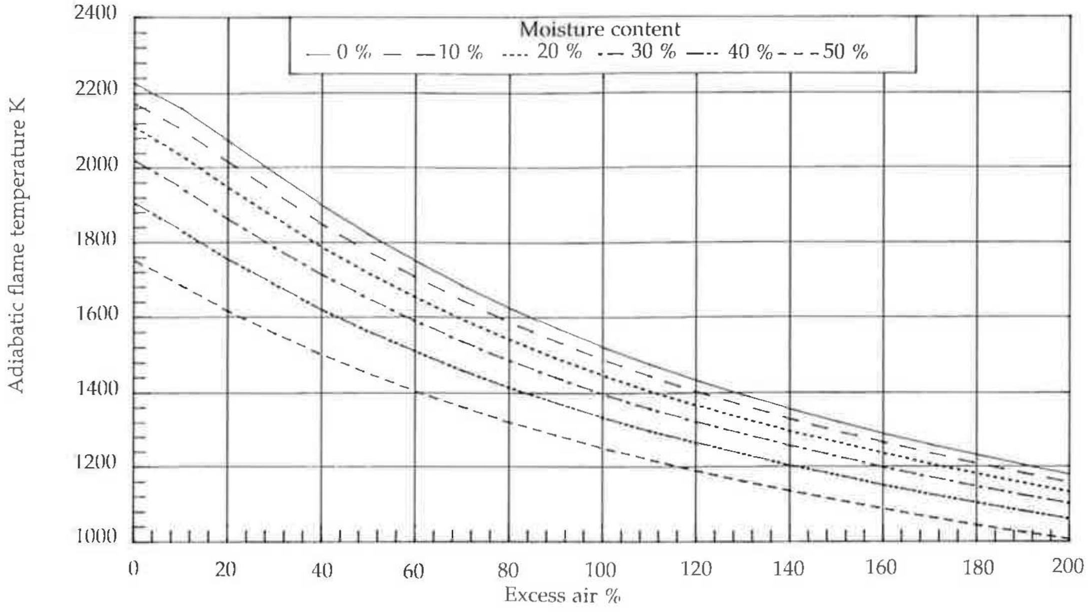

Figure 3 Adiabatic flame temperatures for typical woody biomass (ash-free)

The basic governing equation for the adiabatic flame temperature can be expressed from the heat balance as:

$$m_t \int_{t_a}^{t_{ad}} C_p^* \, dt = NCV \qquad \textbf{(22)}$$

Where C_p^* is the 'effective heat capacity' of the combustion products and incorporates effects of dissociation and temperature, and t_a and t_{ad} are the reference and adiabatic flame temperatures respectively. The mass of the gaseous combustion products (excluding ash) per unit mass of fuel is m_t and for typical woody biomass is given by:

$$m_t = 5.894\,(1 + \frac{A_e}{100})\,(1 - \frac{C_m}{100} - \frac{C_a}{100}) + (1 - \frac{C_a}{100}) \qquad \textbf{(23)}$$

If the effective heat capacity C_p^* can be expressed in a form which is independent of the temperature then equation (22) can be integrated to give, for a reference temperature of 298K:

$$t_{ad} = \frac{NCV}{m_t\, C_p^*} + 298 \qquad \textbf{(24)}$$

The following correlation for the effective heat capacity C_p^* – in terms of excess air and moisture content of the fuel – closely approximates to the data given in Figure 3 for typical woody biomass:

$$C_p^* = (1 - f_{H_2O})\,\{1.457 - 0.0597(A_e + 1.03)^{0.324}\} + 1.594 f_{H_2O} \qquad \textbf{(25)}$$

where the mass fraction of the water vapour f_{H_2O} – resulting from the moisture in the fuel – in the combustion products is given by:

$$f_{H_2O} = \frac{C_m}{100\, m_t} \qquad \textbf{(26)}$$

These equations can be used to obtain a very close approximation of adiabatic flame temperature and include effects of dissociation. The range of applicability of these equations is for excess air up to 200% and moisture contents up to 50%. The adiabatic flame temperature calculated from equations (23), (24) and (25), within the range of applicability, differs from rigourously calculated values by a maximum of 24 K at stoichiometric air and 30% moisture content. The difference decreases rapidly with excess air and the average difference over the entire applicability range is 5 K.

If the rate of heat extraction E_h (expressed on the basis of one kg of fuel) in a combustor is known, then the maximum temperature possible in such a system can be calculated from:

$$t = \frac{NCV - E_h}{m_t\, C_p^*} + 298 \tag{27}$$

The adiabatic flame temperature is never realized in practice because:

- there is always some heat loss from any combustion system. In fact in most systems heat is intentionally extracted from the burning fuel and air mixture;
- the residence times in combustors may not be long enough to allow combustion products to reach a state of equilibrium; and
- in combustion systems some fuel may remain unburnt.

In some refractory furnaces with no heat absorption surfaces, such as pre-combustor units, heat losses can be small. For these units, adiabatic flame temperatures may be used to define refractory specifications and maximum likely air requirements to maintain combustion chamber temperatures within limits of the refractory chosen.

EQUIPMENT FOR BIOMASS COMBUSTION

Introduction

The nature of fuels from biomass is significantly different from that of more established solid fuels such as coal and coke. The combustion of biomass poses particular problems compared with solid fossil fuel combustion, yet also displays certain advantages. Hence it is rarely possible to use a traditional fossil fuel combustion system without at least some modification.

For efficient heat release during combustion a certain minimum grate area and combustion volume (that is, residence time) are required. The grate area and furnace volume need to be matched to give a furnace of a given output. If the furnace volume is too small in relation to the grate, then combustion will not be completed in the furnace and the heat transfer surfaces could be damaged by flame impingement. If the grate area is too small then it will not be possible to maintain the rated heat release. These aspects are discussed in detail below. There are estimates of furnace dimensions for various heat release rates in the literature. The results for biomass fuels are summarized in Table 5. These figures serve as a guide only and are dependent on the particular design of combustor which is employed.

Table 5 Combustion conditions in different furnaces

Reference	Grate area kW/m^2	Combustion volume kW/m^3
Breag *et al.* (1986)		210 – 280
Tillman *et al.* (1981)		
pile burning	2360	
Livingston *et al.* (1990)	800 – 850	
Trinks and Mawhinney (1951)		
poor mixing		60
fair mixing		220
Tillman (1987)		
inclined grate	970	140
wet cell	1560	210
spreader stoker	2830	140 – 210
ETSU (1990)	500 – 700	

Note: Figures have been rounded to the nearest 10 units in converting to uniform units

Adaptation and operation of systems designed for coal-firing

Many biomass combustion systems are derived from those designed for coal-firing. While these may at first sight appear to be ideally suited to biomass fuels, there are very important differences which must be taken into account. Where coal-fired equipment is being used with biomass fuels certain modifications to the design and operational procedures may have to be carried out, and, ideally, equipment which has been proven on biomass should be used. The following paragraphs detail some of these factors.

Calorific value and fuel density

Biomass has a gross calorific value of only 19 MJ/kg on a dry ash free basis compared to 36 MJ/kg for high rank coals. In addition it has a lower density than coal, so on a volumetric basis the calorific value is only 13.5 GJ/m^3 compared to about 50 GJ/m^3 for high rank coals. Hence for a given grate area and depth of fire-bed, there will be a lower inventory of biomass fuel in the furnace and therefore it will be harder to sustain as high a heat release rate in the bed as with coal.

The adiabatic flame temperatures for dry biomass fuels are only slightly less than for fossil fuels. However, in practice, because of high moisture content and the relatively high excess air levels employed in some systems, combustion temperatures for biomass fuels are lower than for coal. Nevertheless, temperatures are high enough to produce high grade heat such as superheated high-pressure steam.

The feed system will have to handle a volumetric feed rate three to four times higher than for fossil fuels. It is not usually practical merely to increase the speed of conveyors and augers; a larger size is often required.

These factors mean that a significant derating of a conventional system is required on the basis of reduced calorific value alone. Moreover, there are other factors which reduce the performance further.

Moisture content

As was shown earlier, the moisture content of freshly cut wood is approximately 50%. After air drying it may reduce to 25%, but this is still high enough to pose problems in unmodified combustion systems.

Dry fuels may be burned directly in a combustion chamber, such as a boiler furnace, with heat transfer surfaces present. Wet fuels require sufficiently high temperatures and combustion volumes to dry the fuelwood before combustion. In this case, refractory lined furnaces are used before the heat transfer part of the system. Moreover, some refractory is usually required to ignite the fuel. Supplementary firing with a fossil fuel may be required at very high moisture contents.

Ignition problems mean that underfeed systems (systems in which fresh fuel is covered by a top layer of burning char) designed for use with coal, such as chain grate and retort stokers, are difficult to operate successfully on biomass.

Evolution of volatiles

Biomass fuels have a high volatiles content (75–85% compared to 7–35% for coals) and hence their reactivity is somewhat higher. After the fuel has dried, the volatiles are evolved very rapidly and at a lower temperature than for coal (ETSU, 1990). Much more of the combustion occurs in the gas phase above the fire-bed. This requires a larger furnace volume than a coal-fired system of the same rating.

An additional effect is seen with batch fired systems. When a fresh load of fuel is added, the volatiles are released in a short period of time once the fuel has dried. There is a rapid heat release in the furnace volume which then dies off leaving the char to burn at a more steady rate. If the air supply is adjusted to give complete combustion of the volatiles, then there will be too much air for efficient combustion once these have burnt off. The temperature of the gases, rate of heat transfer and efficiency will therefore vary with fuel feed times.

Ash content

The ash content is relatively low in fuelwoods. This is advantageous in that the ash handling system can be correspondingly smaller. However, certain grate systems rely on an ash coating to maintain a low grate temperature.

Consistency of fuel

Coal is usually graded within controlled limits and the shapes of the particles or lumps are fairly consistent. The moisture content is relatively low and the material flows reasonably easily.

Fuelwoods and forestry waste often contain twigs which can form a mesh which blocks feed mechanisms. Even if irregularly sized particles such as twigs are screened out, the fuel is prone to bridging and blockage in hopper mechanisms.

Other fuels such as rice husks are dry and of consistent size and shape. Normally they flow easily, but if mixed, for example, with rice bran the flow characteristics are changed. This illustrates the need for careful control of fuel quality and consistency.

Types of combustion system

Grate

Grate systems range from the traditional designs to continuously fed inclined grates and spreader-stoker systems. Chain grates have been used for burning biomass, but have been found to be unsuitable if designed for coal combustion (ETSU, 1990). These systems also include hand-fired flat grate systems.

An example of a horizontal fixed grate is shown in Figure 4. This is the most common type of biomass combustion system. The grate consists of a horizontal cast-iron grid onto which the fuel is fired. Primary air is fed under the grate and is supplemented by over-bed secondary air. This type is suited to hand-firing of wood logs for small-scale plant. They can also be automatically stoked with particulate fuels, though an inclined grate is more suited, as shown in Figure 5.

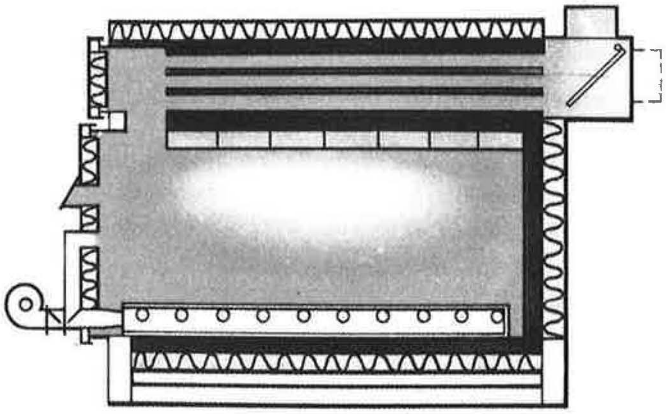

Figure 4 Flat grate (Sarwar *et al.*, 1992)

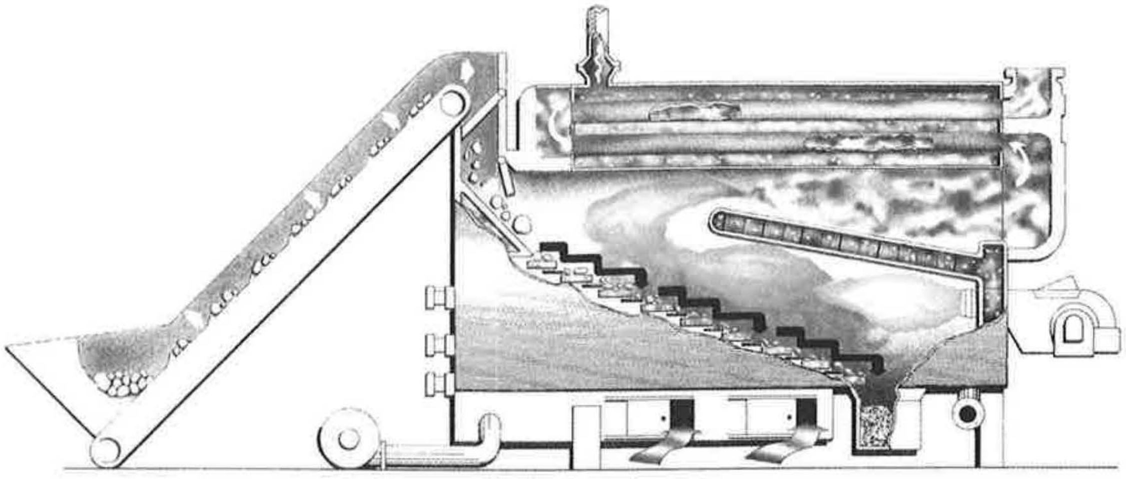

Figure 5 Sloping grate (Sarwar *et al.*, 1992)

Inclined grates are used for a wide range of sizes from about 1 MW_t to over 100 MW_t. As the fuel progresses down the grate, drying, evolution of volatiles and burning of char take place. The ash is removed at the bottom of the grate.

Rate of heat release is controlled by primary or under-fire air which would typically be at stoichiometric levels or below. Gas-phase combustion is controlled separately by the secondary or over-fire air. These systems are often operated as separate pre-combustion chambers and tertiary air is sometimes admitted in the final chamber to burn off the remaining gases.

In some grate systems the secondary air is introduced tangentially into a cylindrical chamber above the grate and the burning gases follow a helical path. These are sometimes called cyclonic burners.

For large systems, spreader stokers are used. Some pre-combustion reactions occur while the fuel particles are in suspension, but most of the combustion takes place on the grate. As with inclined grates the system may, if required, be operated with sub-stoichiometric primary or under-fire air, the gases being burnt separately above the grate.

Where automatic firing is used, moving grates are often employed and give greater control over fuel burn rates and residence time. The grate consists of either a chain-like conveyor or a series of oscillating bars which 'walk' the fuel through the combustion zone.

Under-feed stokers

Under-feed stokers are similar to coking stokers used for coal combustion and are suitable for high moisture content fuels. However, certain differences are necessary in order for these stokers to operate effectively. A larger diameter screw feeder is required to maintain a sufficiently high feed rate and air must be supplied on the outside of the retort and above the fire-bed to burn the volatiles efficiently. They are used in the range of 10 to 5 000 kW_t. An example of such a system is shown in Figure 6.

Fluidized bed combustors

Fluidized bed combustors are only suited to particulate and chipped fuels. The base of the combustion chamber consists of a distributor plate through which the combustion air passes. Above the plate is a layer of sand. When the air passes through the bed, the sand becomes fluidized. Combustion is initiated by heating the sand from an auxiliary burner fitted either externally or

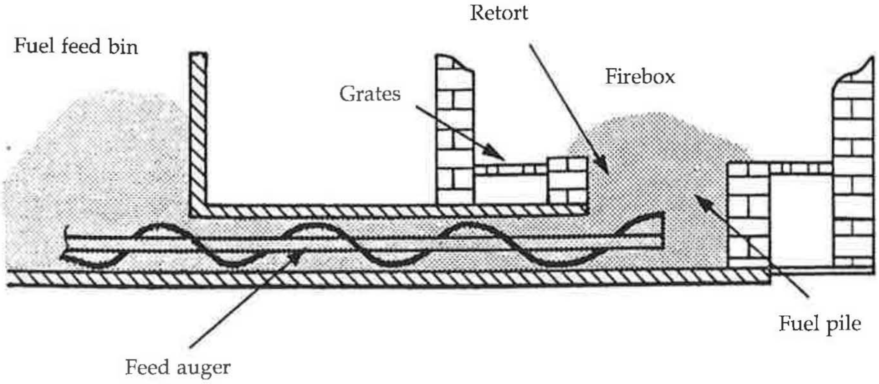

Figure 6 Underfeed stoker (Mahin, 1991)

above the bed. Once the system is hot, fuel is fed directly into the bed or introduced from above. Fluidized beds allow close control of the combustion conditions and permit high heat transfer rates in the bed. However, they are relatively new in biomass technology and are mainly available only for larger sized boiler plants.

Care must be taken to keep temperatures below the fusion temperature of the bed material (ash and sand). Fluidized bed systems typically operate at bed temperatures of 850–900 °C. A proportion of heat released during the combustion of fuel is extracted by heat transfer surfaces immersed in the bed. Because of the high volatile matter content of biomass fuels, combustion is not completed in the bed and secondary air is added in the free-board (space above the bed of fluidized material). The proportion of air through the bed compared to that added in the free-board depends upon the operating temperatures and extent of extraction of heat in the bed.

Suspension burners

Suspension burners are suitable to burn particulate wood wastes and agricultural residues typically of regular shape and size. The fuel is entrained in the combustion air and the fuel/air mixture introduced into the furnace. A flame, analogous to an oil flame, is generated in the combustion chamber and the fuel particles remain entrained until completely burnt.

Cyclonic suspension burner systems are available which consist of a cylindrical chamber where the air/fuel mixture is introduced tangentially and the gases follow a helical path.

If properly designed, these combustors provide good mixing between fuel and air and have high combustion efficiencies. However, fly ash is produced and this must be taken into account in the specification of the heat transfer equipment.

Pre-combustors

Pre-combustor systems are particularly suited for fitting to boiler equipment designed for oil-firing. The system consists of a pre-combustor chamber where biomass is converted with sub-stoichiometric quantities of air. The resulting high-temperature gas contains combustibles, and is mixed with secondary air at the exit of the pre-combustor to achieve complete conversion of fuel to products. This second stage of combustion can take place in the combustion chambers of a boiler plant or, for other applications, in a purpose-built secondary combustion chamber.

In a recently published survey (Sarwar *et al.*, 1992) availability and types of biomass-fired combustion and ancillary equipment are detailed.

Operation

Due care must be given to the operation of different systems and, in particular, batch-fired furnaces. The feed must be regular and frequent, otherwise the fuel bed will flare up and possibly overheat the furnace and certainly reduce efficiency. Furthermore, the wide variations in heat release will lead to large variations in heat output of the system. The furnace doors should be closed after each feed so that the control of air to the furnace can be properly maintained. If a furnace door has to be opened to maintain a sufficient heat output then the furnace is being run beyond its design capacity, with a consequent loss of efficiency and shortening of the life of the equipment.

MEASUREMENTS IN COMBUSTION EQUIPMENT

As explained in the section on *Calculations of air requirements, theoretical composition of flue gases and adiabatic flame temperature*, the gases found in flue gases after complete combustion of a stoichiometric fuel/air mixture, are carbon dioxide, water vapour and nitrogen. In practice, almost all combustion equipment is operated with excess air, therefore oxygen is present as well. However, the combustion will never be entirely complete and small quantities of carbon monoxide will exist. High values of carbon monoxide in the flue gas can result from flame impingement on cold surfaces in the combustion systems and consequent quenching of the reactions in the burning gas. Knowledge of the composition of the flue gas in terms of carbon dioxide, carbon monoxide and oxygen is essential for the accurate calculation of excess air and thermal efficiency.

Sample preparation

The position of the flue gas sampling point is important. If the sampling point is too far up the flue there is a danger that leaks into the system would dilute the flue gas. In general, the sampling point should be as near to the exit of the combustion chamber as possible while still permitting adequate mixing of the flue gas.

The flue gas sample will contain water vapour and possibly some condensable tars and smoke particles. All these can condense inside the sensitive detection equipment and cause damage. A typical sample conditioning system to protect the measuring instruments is illustrated in Figure 7.

The sample is taken from the centre-line of the flue and bubbled through water, with a few drops of dilute sulphuric acid added, contained in a Drechsel bottle. The bottle is kept cool with ice to condense out tars and water vapour present in the flue gas sample. The acid prevents the absorption of carbon dioxide in the water. The flue gas sample leaving the bottle is therefore free of tar and most of the water vapour.

The remaining small quantity of water vapour is adsorbed in a tower packed with anhydrous calcium chloride or anhydrous calcium sulphate. Other desiccants can be used as long as they do not react with any of the gases in the sample.

The suction pump should be capable of drawing the sample gas through the entire sampling line at the rate specified in the instructions for the gas analysis equipment. It is essential that a fine particle filter is placed at some point before the analysis equipment. Although many analysers have filters built in, they should only be relied on as a backup. The sampling line itself should provide a clean, dry gas suitable for analysis. Proprietary and tailor-made equipment for sampling and conditioning of flue gases for analysis is available.

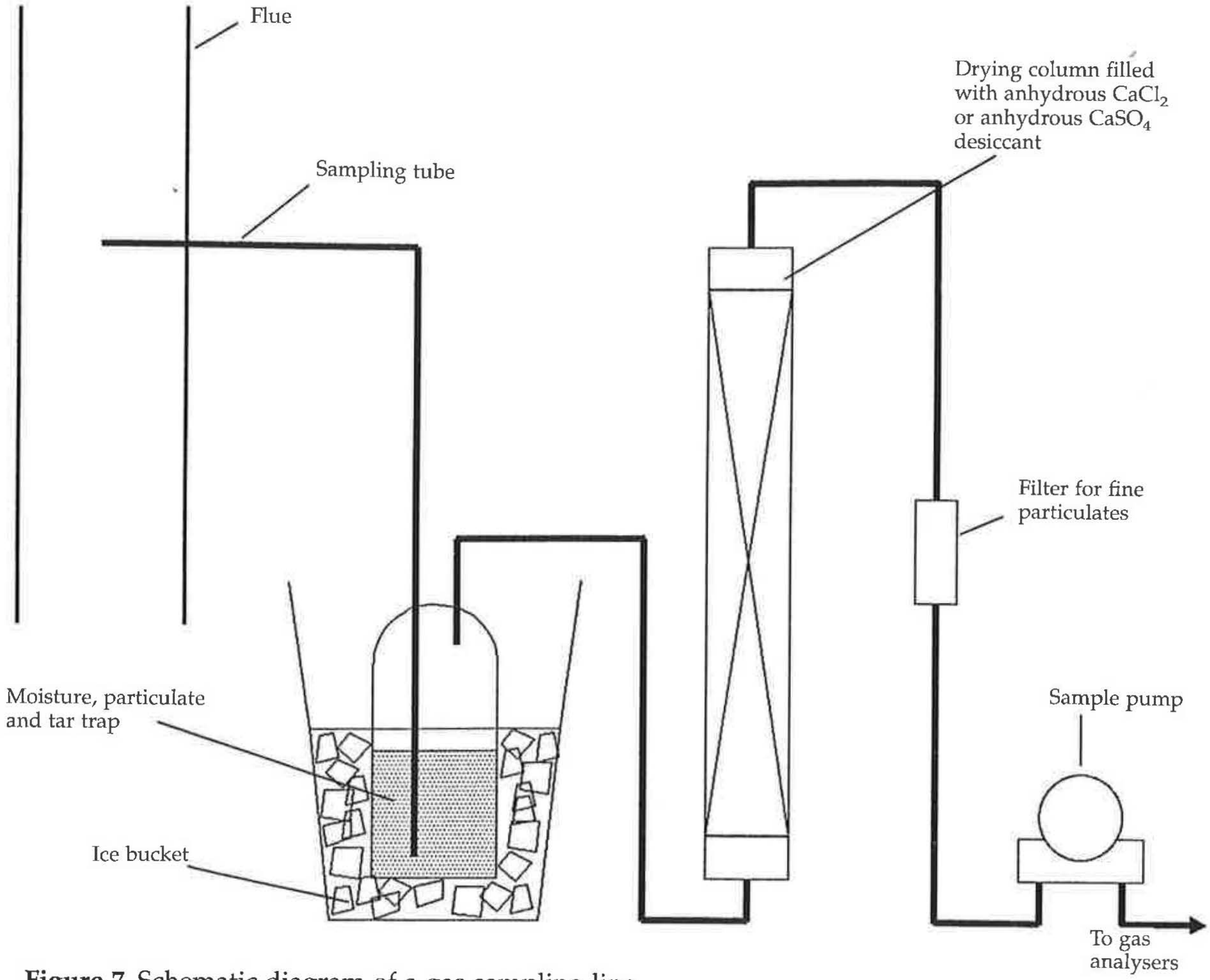

Figure 7 Schematic diagram of a gas sampling line

Gas analysis

A large number of different methods of gas analysis exist, each with their own advantages and limitations. Different techniques showing their applicability to different gases are summarized in Table 6.

Table 6 Gas analysis techniques

Method	Gas	Sample type	Typical accuracy*
Wet reagent (Orsat)	CO_2; O_2; CO	batch	±0.2%
Dry reagent (Dräger)	various	batch	±5%
Gas chromatography†	any	batch	
Infra-red†	CO_2; CO; NO	continuous	±1%
Para-magnetism†	O_2	continuous	±0.4%
Electro-chemical	CO; O_2	continuous	CO ±2.5%; O_2 – 0% + 4%
Zirconia probe†	O_2	continuous	±0.8%

Notes: * % of full scale deflection under good operating conditions except for Orsat where accuracy is given as absolute error

† instrument can be interfaced to data-logging equipment

Wet reagent

The most common version of the wet reagent type of apparatus is the Orsat apparatus. The reduction in volume of the individual constituents is measured after they have been removed separately and in turn by absorption in liquid reagents. The apparatus is illustrated in Figure 8.

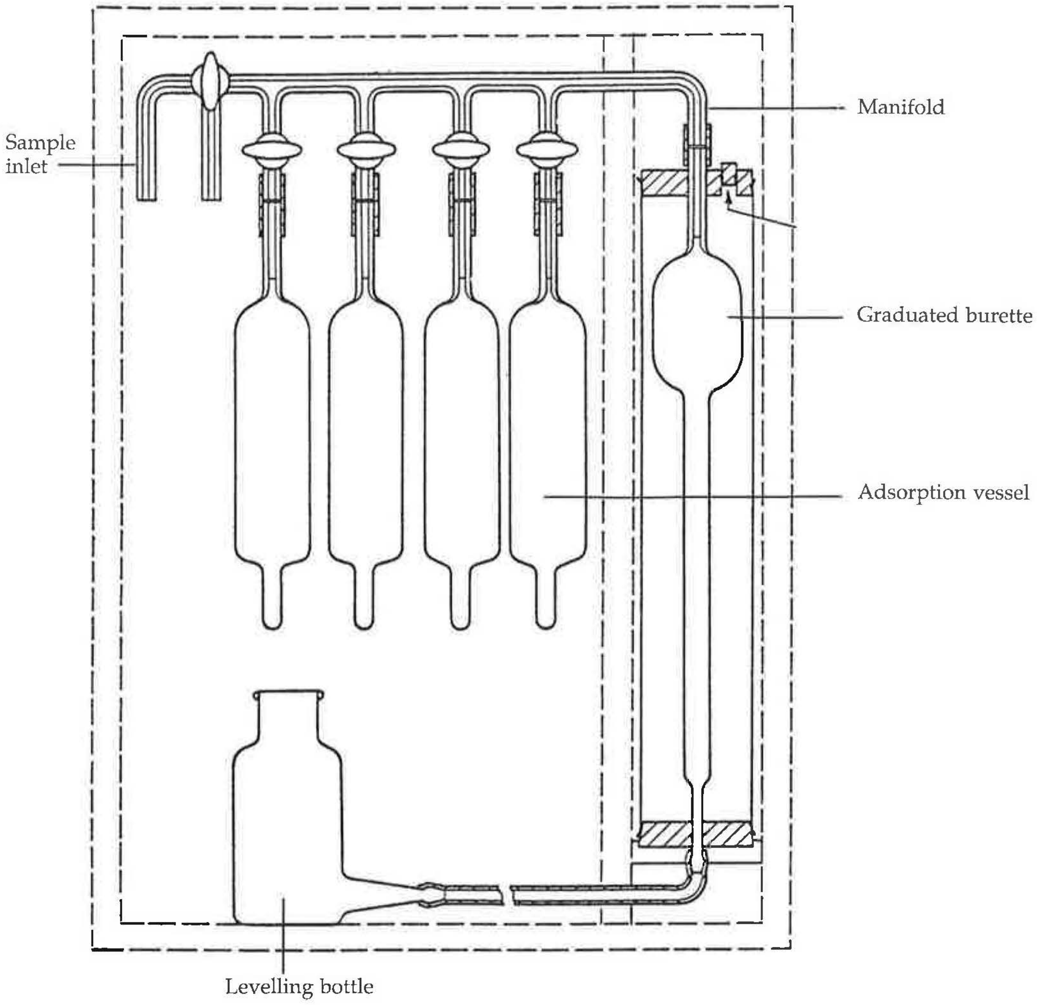

Figure 8 Orsat apparatus (BS1756: Part 2: 1971)

The reagents used are as follows:

Carbon dioxide	Potassium hydroxide solution
Carbon monoxide	Ammoniacal cuprous chloride solution
Oxygen	Alkaline pyrogallol solution or acid chromous chloride solution

A measured volume of sample gas is drawn into the gas burette and passed into the carbon dioxide-absorbing reagent. The sample is then returned to the burette. This procedure is repeated until no further volume change is noted. The process is repeated for the other two gases. It is essential that the analysis is carried out in the sequence: CO_2, O_2 and CO. For example, if the sample is passed through ammoniacal cuprous chloride before removing the CO_2, both CO_2 and CO will be absorbed. Full details are given in BS 1756:Part 2:1971.

Other gases can be analysed using appropriate reagents. The equipment can also be used to determine hydrogen and methane content using a heated platinum wire in a combustion pipette or by absorption of the hydrogen on palladium.

The apparatus has the advantage of being reasonably accurate, (0.2% absolute accuracy) portable and capable of analysing all the important gases in one apparatus. However, it is only a batch analyser, it contains fragile glassware, is time consuming and requires operator skill to obtain an accurate reading. The reagents need to be handled with care as they are harmful or corrosive. A method which mitigates these disadvantages at the expense of accuracy is the Fyrite apparatus for carbon dioxide and oxygen determination. Conversely, other more comprehensive and accurate (though more cumbersome) systems such as the Haldane apparatus can also be used (BS1756:Part 3:1971).

Dry reagent

The measurement of low concentrations of a wide range of gases can be achieved using gas detector tubes. Each tube is specific to one gas and is calibrated over a limited range of concentrations. The disposable glass tube is packed with a solid substrate containing a chemical reagent and an indicator. Other reagents may be present to adsorb other gases which may affect the reading. A given volume of gas is drawn through the tube using a specially designed hand pump. The indicator changes colour and the length of the stain produced or the colour of the stain is used to estimate the gas concentration.

Gas detector tubes were originally designed for occupational safety use and not for combustion monitoring. Different samples have to be taken for each gas, the tubes are not particularly accurate and the hand pump can be difficult to use. Nevertheless, the apparatus is very compact and easily portable and only methods such as gas chromatography (described below) are capable of examining such a wide range of gases.

Gas chromatography

Extensive literature has been published on the technique of gas chromatography (Perry, 1981; Sewell and Clarke, 1987; Willett, 1987) and only a brief description can be included here. Gas chromatography separates mixtures by taking advantage of their components' differential distribution between a mobile gas phase and a stationary phase.

A small sample of the gas to be analysed is injected into a stream of a carrier gas such as helium. The gas mixture passes through a column packed with a solid adsorbent or a thin film of liquid on a solid support. Different gases pass through the column at different rates and are detected at the column exit at different times as an impurity in the carrier gas. The concentration variation of the different gases is measured in the detector whose output produces a trace known as a chromatogram. From this trace the absolute concentrations of the gases in the sample can be calculated. A typical gas chromatograph system is illustrated in Figure 9.

Successful separation of gases is dependent on the choice of column material and configuration and it is recommended that the column manufacturer's advice be sought on a particular application. Modern gas chromatographs are automatic or semi-automatic and include sophisticated signal processors which can output the gas composition directly. They can be used to analyse virtually any gas mixture and an accurate reading can be obtained in a few minutes. However, they are not suitable for routine combustion monitoring as they are expensive and not portable and require highly trained operators.

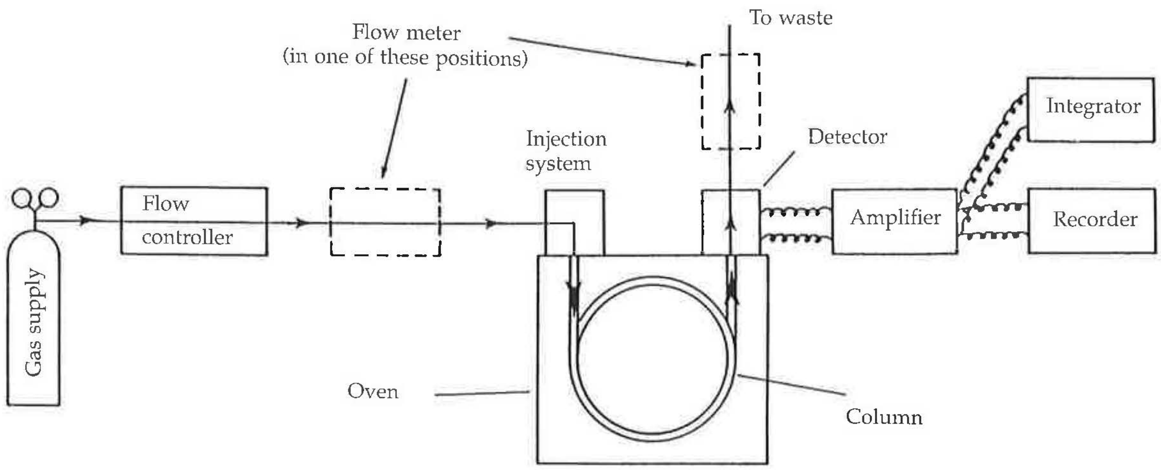

Figure 9 Block diagram of a gas chromatograph (Willet, 1987)

Infra-red analysers

Infra-red analysers use the property of the hetero-atomic gases to absorb selectively certain bands of infra-red radiation. Infra-red light is filtered and passed through a tube through which the sample gas is flowing. At the other end of the sample tube an infra-red detector measures the amount of radiation passing through the gas. The signal is compared, either sequentially or simultaneously with that passing through a reference gas. The latter is usually the ambient atmosphere scrubbed of the gas being detected. The selectivity of the instrument for a particular gas is achieved by passing the light beam through a series of filters. The different configurations are discussed further in Coombes and Stroud, 1982.

These instruments are highly accurate and measure continuously with response times of the order of one second. They require little operator experience and are available as rack mounted or battery powered portable units. An example of such a unit is shown in Figure 10.

Figure 10 Infrared analyser (*Courtesy of ADC*)

Infra-red analysers do require regular calibration against standard mixtures. The instrument zero is set using pure nitrogen, or, in the case of a carbon monoxide monitor, ambient air which is passed through a catalytic converter installed in the instrument. The carbon dioxide monitor can also be zeroed using dry air which has been passed through a tower of soda lime, or bubbled through a potassium hydroxide solution to remove the carbon dioxide and subsequently through a column filled with a suitable desiccant to remove water vapour. Calibration gases can be purchased from specialist gas suppliers. Suitable concentrations for calibration are 80% of full-scale deflection on the instrument's most sensitive range, or a concentration close to that expected in the sample gas.

Paramagnetic oxygen analysers

Oxygen is unique among common gases in that it is strongly paramagnetic. When placed in a non-uniform magnetic field it is attracted towards the stronger part of the field. Diamagnetic gases such as nitrogen are repelled by the field.

Practical oxygen analysers consist of two nitrogen-filled glass spheres suspended in a dumb-bell arrangement held in a non-uniform magnetic field (*see* Figure 11). The spheres are repelled slightly from the field. When the surrounding gas contains oxygen the field is altered and the spheres are pushed further out of the field. This deflection is measured optically and is counteracted electrostatically or electromagnetically; the current required to return the spheres to their zero position gives an indication of the oxygen concentration (Tipping, 1975)

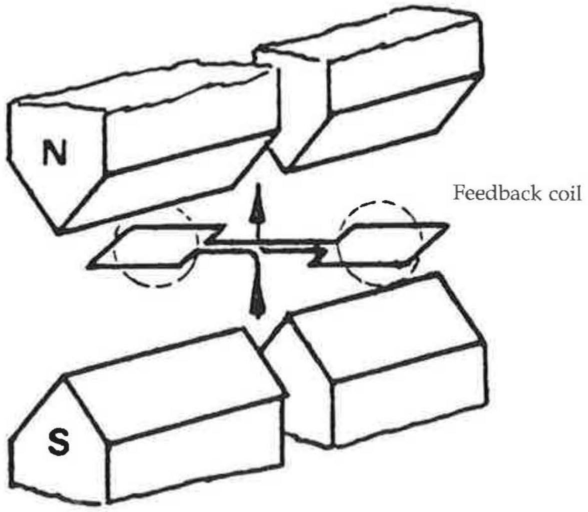

Figure 11 Oxygen measuring cell (*Courtesy of Servomex*)

Oxygen analysers are zeroed using pure nitrogen, and the span can be set with sufficient accuracy for combustion purposes using pure, clean air which has an oxygen content of about 20.9%. They have similar advantages to the infra-red analysers described previously. An example of a commercially available analyser is shown in Figure 12.

Figure 12 Paramagnetic oxygen analyser (*Courtesy of Servomex*)

Electro-chemical analysers

Electro-chemical analysers are used to determine oxygen and carbon monoxide concentrations. A typical sensor consists of an anode, electrolyte, a diffusion barrier and an air cathode. In the oxygen sensor, the oxygen diffuses to the cathode and is reduced to hydroxyl ions, while the metal anode is oxidized. In the carbon monoxide sensor, the gas is oxidized at the cathode. The voltage change across the electrode is proportional to the gas levels. The selectivity of these instruments is reasonable, except that the carbon monoxide sensor is very sensitive to sulphur dioxide. The sensors have a limited life, particularly in tropical conditions.

The sensors can be combined into a single piece of equipment which also reads flue gas temperature and incorporates a microprocessor. The equipment computes and gives a direct reading of equipment efficiency. Such an instrument is shown in Figure 13. The fuel type is entered on the instrument control panel and the probe is inserted into the stack of the combustion equipment. The instrument displays oxygen, carbon monoxide and stack temperature, from which it calculates the efficiency of the combustion system for typical solid, liquid or gaseous fossil fuels, on the assumption that all the carbon in the fuel is converted to carbon monoxide or carbon dioxide. The programme in the instrument does not contain separate data to calculate efficiency of biomass-fired equipment. However, these efficiencies can be derived from knowledge of the oxygen and carbon monoxide levels and the flue gas temperatures.

Figure 13 Electro-chemical analyser (*Courtesy of Neotronics*)

Zirconia probe oxygen analysers

Zirconia probe oxygen analysers are an extension of the electrochemical principle described previously. They are being used increasingly in industrial applications and especially at high temperatures. At the heart of the sensor is a solid electrolyte of zirconia (ZrO_2) with a small amount of ytteria (Y_2O_3) dissolved in the crystal structure. At temperatures over 600 °C this material conducts oxygen ions. (Kocache *et al.*, 1984) One design of a zirconia cell is shown in Figure 14.

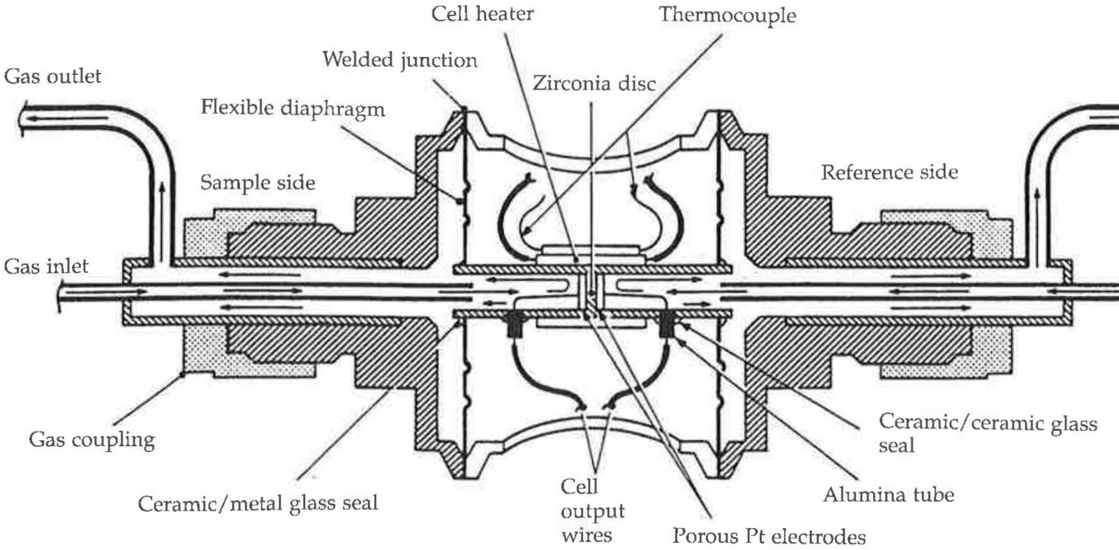

Figure 14 Zirconia oxygen sensor (Kocache *et al.*, 1984)

Air is used as the reference gas; hence the sensor produces a zero signal at 21% oxygen rising linearly to a maximum at 0% oxygen. The sensor is fitted to a flange on the flue ducting itself. The gas sample is drawn through a sintered filter on a probe in the flue, passed through the sensor and returned to the flue.

These devices are accurate, robust and particularly suited to permanent monitoring and/or control of a combustion process. However, they are expensive and require a clean dry air supply as the reference gas.

Recommendations

For accurate combustion monitoring with portable equipment, the infra-red and paramagnetic analysers are recommended. If these are not available, or when calibration gases cannot be obtained, the Orsat apparatus or Fyrite equipment have been found to give reliable results.

Measurements of environmental pollutants

Combustion systems are responsible for a variety of gaseous emissions which affect the environment both on a local and a global scale. Many of these effects are complex and not fully understood; these issues are beyond the scope of this publication.

However, monitoring of the more important of these pollutants, in certain circumstances, may be required on legislative and environmental health grounds. Amongst others, these include oxides of nitrogen (NO and NO_2 collectively termed NO_x) and oxides of sulphur (SO_2 and SO_3), and hydrocarbons which include polycyclic aromatic hydrocarbons (PAH). Knowledge of the concentration of these gases is not required for calculation of the combustion and thermal efficiencies of equipment as they appear in very small quantities.

Polycyclic aromatic hydrocarbons comprise the largest class of known environmental carcinogens; some, while not carcinogenic, may act as synergists. Combustion processes are the dominant source of these compounds (Bartle, 1991). Biomass-fuelled equipment is often used for heating process air for food products and there the potential exists for PAHs, generated by combustion, to taint the foodstuffs being processed, should they pass into the process air stream. For these applications equipment should be designed to avoid contamination of food products with PAH.

Because of the low concentrations of SO_2, NO_x and PAHs in the combustion gases, care in sampling and analytical techniques is required.

Oxides of sulphur

Sulphur dioxide (SO_2) can be measured with infra-red analysers. The sample methods should recognize that SO_2 is soluble in water. Techniques to remove water without altering concentrations of SO_2 include: bubbling sampled gas through orthophosphoric acid (mixed with phosphorus pentoxide); using drying towers filled with proprietary desiccants based on phosphorus pentoxide; and purpose built proprietary sample drying systems which rely on 'Peltier' effect cooling elements. Care is taken in the design of cooling element-type systems to keep the water and gas phases separate in order to minimize loss of water-soluble gases. The sampling line should be heated to avoid condensation and should be made from materials which do not cause chemical changes in the sample. Equipment for continuous monitoring of sulphur trioxide (SO_3) is also available (Jackson *et al.*, 1981).

Oxides of nitrogen

Similar sampling and sample conditioning requirements apply for measurements of NO_x. NO_x can be measured either by infra-red or chemiluminescence analysers. Both types of analyser measure concentrations of nitric oxide (NO). The chemiluminescence analysers are based upon the principle that the reaction of nitric oxide (NO) with ozone (O_3) produces light; the intensity of light produced is related to the concentration of NO. For measurements of total NO_x, catalytic converters which convert nitrogen dioxide (NO_2) to NO, can be incorporated into both types of analysers or supplied as external modules. Discrimination between NO and NO_2 is achieved by allowing the sample either to flow through or to by-pass the converter. For results to be meaningful, concentrations of SO_2, SO_3 and NO_x should be reported on the basis of accepted conventions.

Polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbon compounds are very difficult and time consuming to measure. The situation is made worse by the fact that a proportion of these compounds exist in adsorbed form on small particulate matter. They can also condense in the sampling lines if proper procedures are not followed. For PAH measurements isokinetic sampling techniques are employed. This requires that the velocity of the gas entering the probe be maintained at a rate equal to that of the surrounding gas. Care in the design of the sampling nozzle is necessary to avoid distortions in the concentration of particulates in the sampled gas. The sampling systems also include temperature controlled filters, polymeric resins for adsorption of gaseous PAHs, cooling systems for collecting condensable compounds and sample flow meters. PAHs are then collected from the filters, adsorbent and condensate by extraction with organic solvents such as dichloromethane, toluene or cyclohexane. These solvents have been shown to exhibit varying efficiencies in terms of PAH extraction. The extracted samples are processed further to concentrate the PAH compounds. The prepared samples are than analysed by high performance liquid chromatography (HPLC), capillary gas chromatography (CGC) linked to a flame ionization detector or to a mass spectrometer.

Because of the small quantities involved, extreme care and high purity of chemicals are required at all stages of the analytical process. Some of the PAH compounds are photo-degradable and therefore prolonged exposure to light should be avoided during sample storage, sample extraction and sample concentrating steps. Further details of sampling and analytical techniques for combustion generated PAHs can be found elsewhere (Williams, 1990; Benestad, 1986; 1990).

Different PAH compounds have been used as a basis for reporting results and workers have used up to 37 commonly occurring compounds for defining quantities of PAH in the sampled gas. Results have also been reported as tars on the basis of solid matter left after evaporation of solvent. Work carried out under the auspices of International Energy Agency (IEA) for standardization of PAH measurements recommends the reporting of results based on the 15 most dominating PAH compounds occurring in emissions from biomass combustion systems (Benestad, 1990).

Flue gas temperature measurement

Knowledge of the temperature of the flue gas is as important as the flue gas composition. The thermocouple is the most suitable instrument for temperature measurement in furnace systems. Other devices can be used if they are available, provided that accuracy limitations, usable temperature range and convenience are taken into account.

Types of thermocouple

The thermocouple itself consists of a junction of two different types of metal or alloy welded or soldered together. The probe develops an electrical potential which is related to the temperature of the thermocouple. Various combinations of metals have different outputs as a function of temperature. The combinations are denoted by a letter. A few of the common ones are shown in Table 7. For more information *see* BS 1041:Part 4:1966.

Thermocouples have a limited life, especially at high temperatures. It is recommended that manufacturers' advice be sought regarding thermocouple life under specific conditions.

A wide range of digital thermometers suitable for reading the output from different types of thermocouple is available.

Table 7 Common types of thermocouple

Type	Composition	Range	Accuracy	Notes
K	Nickel-chromium +	0–400 °C	±3 °C	General purpose
	nickel-aluminium	400–1100 °C	±0.75%	
T	Copper + constantan	0–100 °C 100–400 °C	±1 °C ±1%	Corrosion resistant
R, S	Platinum/rhodium + platinum	0–1100 °C 1100–1400 °C	±1 °C ±2 °C	High temperature

Errors in gas temperature measurement

When a thermocouple is placed in a duct with hot gas flowing past it, the temperature indicated will not be the true temperature of the gas. The probe will lose heat by radiation to the duct walls and conduction along the thermocouple probe. The indicated temperature will therefore be T_t, which will be greater than the wall temperature (T_w) and less than the gas temperature (T_g).

The true temperature of the gas will be determined by the following heat balance:

Heat radiated from gas to thermocouple
\+ heat convected from gas to thermocouple

=

Heat radiated from thermocouple to flue walls
\+ heat conducted along thermocouple stem

or, in symbols:

$$Q_{gr} + Q_c = Q_r + Q_k \quad \textbf{(28)}$$

Q_{gr} can be ignored for low gas temperatures. Conduction heat losses are usually small, and can be reduced to a negligible amount if the thermocouple is arranged as shown in Figure 15b, with the connecting wires running for some distance along an isotherm in the duct. Additionally, the use of thermocouples of small diameter will reduce conduction losses.

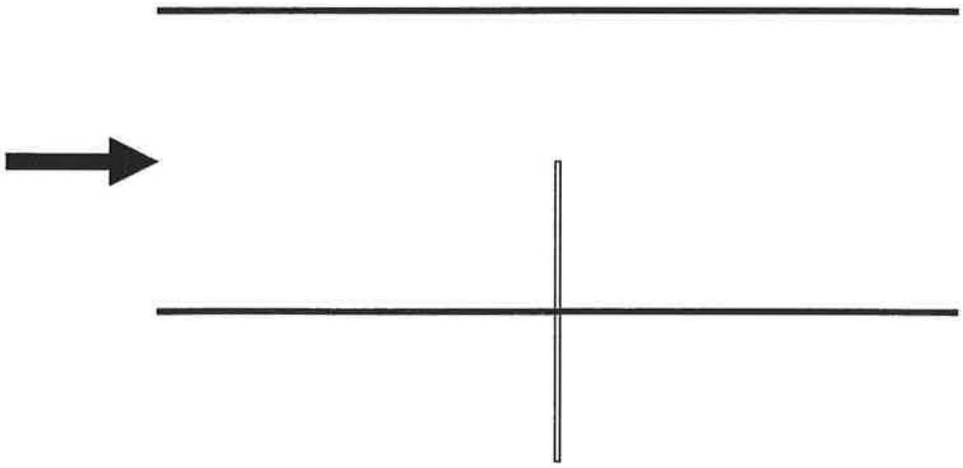

Figure 15a Radial mounting of thermocouple in duct

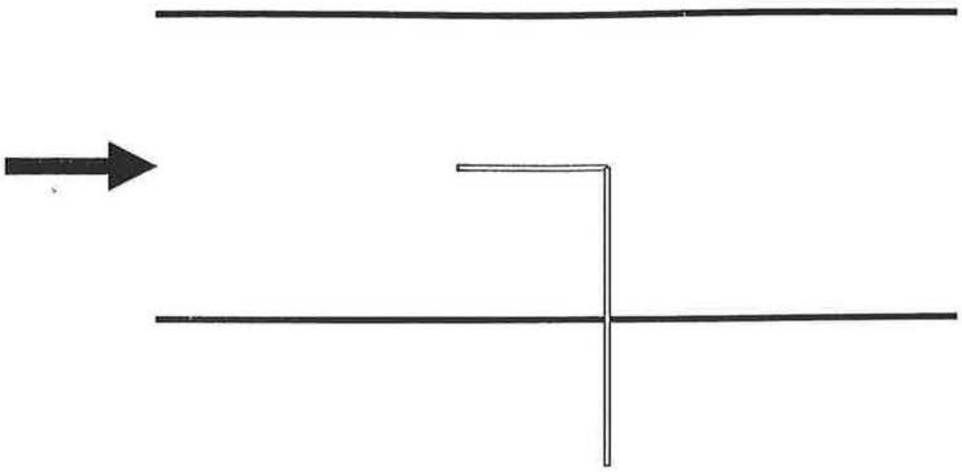

Figure 15b Mounting of thermocouple to reduce conduction losses

The remaining terms can be rewritten as follows:

$$h_c\,(T_g - T_t) = \sigma\,\varepsilon_t\,(T_t^4 - T_w^4) \tag{29}$$

where h_c = convective heat transfer coefficient
σ = Stefan-Boltzmann constant = 5.67×10^{-11} kW/m^2 K^4
ε_t = emissivity of thermocouple
T_g = true gas temperature
T_t = thermocouple reading
T_w = duct wall temperature

All temperatures are thermodynamic temperatures, i.e. they are measured in kelvin.

The convective heat transfer coefficient is found from one of the following correlations (Chedaille and Braud, 1972):

$$Nu = 0.44\,(Re)^{0.5} \text{ for arrangement in Figure 15a} \tag{30}$$

$$Nu = 0.085\,(Re)^{0.674} \text{ for arrangement in Figure 15b} \tag{31}$$

where Nu = Nusselt number = $\dfrac{h_c\ d_t}{k_g}$ **(32)**

and Re = Reynolds number = $\dfrac{\rho_g\ u_g\ d_t}{\mu_g}$ **(33)**

where d_t = thermocouple diameter
k_g = thermal conductivity of gas
ρ_g = density of gas
u_g = gas velocity
μ_g = dynamic viscosity of gas

The following example, which is typical of some industrial installations, illustrates the procedure:

T_t = 225 °C = 498 K
T_w = 150 °C = 423 K
d_t = 0.01 m
ε_t = 0.6
u_g = 1 m/s

The following data is for dry air at 500 K and 1 atmosphere pressure and is a sufficient approximation to the flue gas properties (Rogers and Mayhew, 1980):

$k_g = 4.041 \times 10^{-5}$ kW/m K
$\rho_g = 0.706$ kg/m^3
$\mu_g = 2.67 \times 10^{-5}$ kg/m s

from (33), Re = 264.4

from (30), Nu = 7.154

from (31), $h_c = \dfrac{\mathrm{Nu}\ k_g}{d_t} = 2.891 \times 10^{-2}$ kW/m^{2}K

$$\text{from (29), } T_g = \frac{\sigma\ \varepsilon_t\ (T_t^4 - T_w^4)}{h_c} + T_t = 532.7 \text{ K} = 259.7\ ^\circ\text{C} \qquad \textbf{(34)}$$

It can be seen that there is a significant difference between the measured temperature (225 °C) and the true gas temperature (259.7 °C), of 34.7 °C. At an excess air level of 200% (not untypical in many biomass combustion systems) the incorrect reading would indicate a flue gas loss of about 26% for dry fuelwood. Using the true reading the losses are found to be 29%.

Correcting for errors

If data such as the gas velocity and the duct surface temperature are known, then the above calculations can be carried out to obtain a more accurate estimate of the gas temperature. A more simple, but less accurate estimate can be obtained from graphical correction (BSI: DD65: 1982) given in Figure 16.

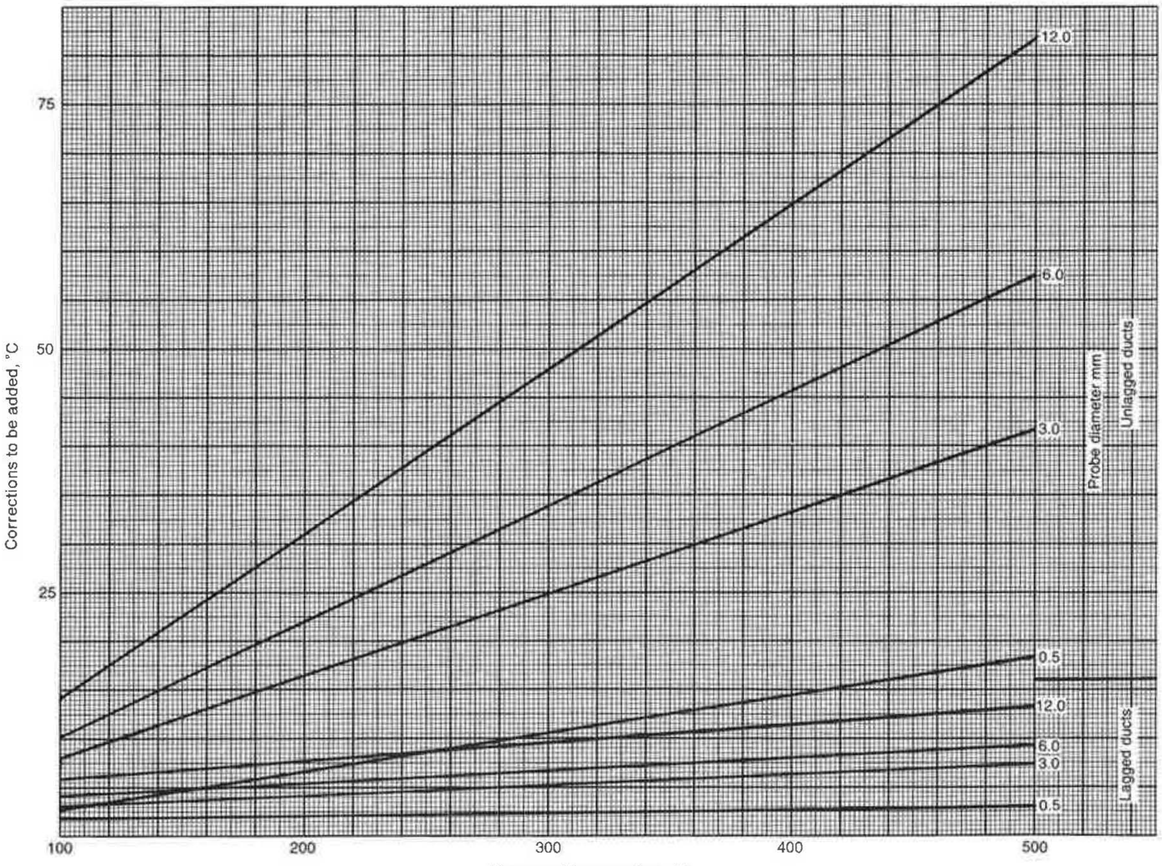

Figure 16 Correction of flue gas temperatures (BSI: DD65: 1982)

There are three practical ways of reducing the measurement error: the size of the thermocouple can be reduced; radiation heat losses can be reduced with radiation shields; and the velocity of the gas passing the thermocouple can be increased.

Reducing the size of the thermocouple increases the convective heat transfer coefficient, h_c, and so reduces the magnitude of the error term in equation (34). Had a smaller (3 mm) diameter thermocouple been used in the above example, the error would have been reduced to 19 °C. This leads to a related solution. For a thermocouple of 'zero' diameter, the error is also zero. By installing several thermocouples (at least four) of different sizes the true temperature may be found graphically. The temperature readings should be plotted against thermocouple diameter. A best fit straight line is drawn through the points and the temperature where the line intercepts the y-axis is the true temperature. An example of this method is shown in Figure 17.

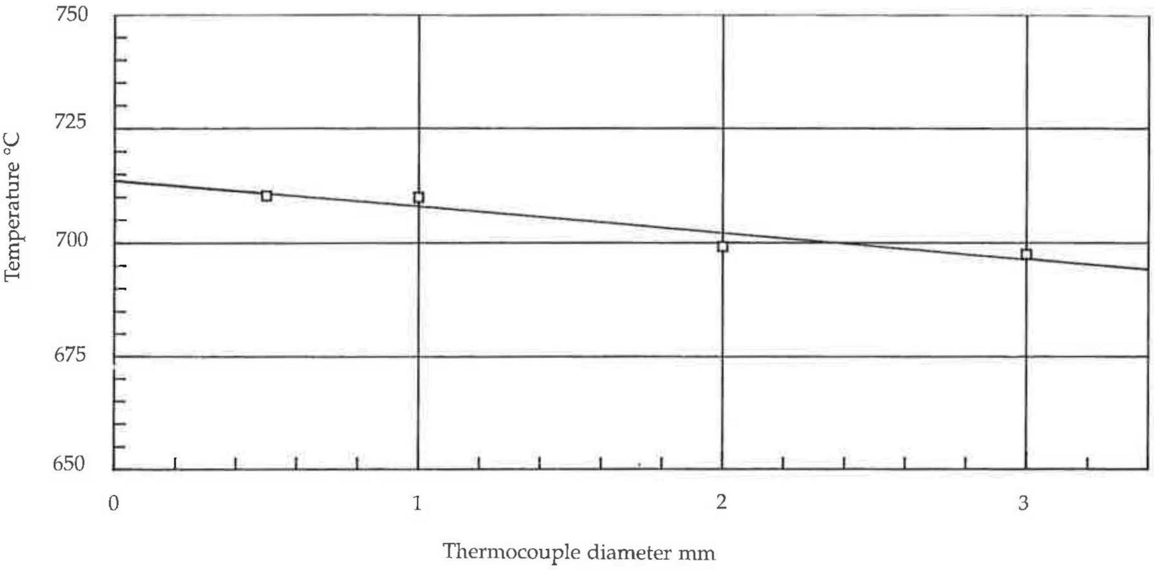

Figure 17 Thermocouple error correction using different diameter thermocouples. Data obtained during tests for combustion of sawdust at NRI (Tariq *et al.*, 1993)

The error can also be reduced by the use of radiation shields around the thermocouple. The shields are heated by the surrounding gas so the temperature difference between the thermocouple and the surface to which it radiates (that is, the innermost shield) is reduced and hence the heat losses from the thermocouple are reduced. An example of the effect of multiple shields around a thermocouple is shown in Figure 18. For most flue gas measurements where temperatures are moderate, three shields would normally be sufficient.

An accurate instrument for gas temperature measurement is the suction pyrometer. This employs a number of the principles mentioned above to reduce measurement error. The thermocouple itself is situated in a tube surrounded by a number of radiation shields. The gas is sucked from the duct through a shielded inlet. The gas is passed over the thermocouple to increase the velocity and hence h_c. Moreover, because the thermocouple is placed in a controlled environment, any residual error can be predicted and eliminated. An accurate measurement of the gas temperature can then be found from a calibration curve. The instrument does have some drawbacks though. It requires periodic calibration and needs time to reach an equilibrium temperature. In addition, water cooling pipes and a suction need to be supplied to the instrument. The main disadvantage in a solid fuel combustion environment is that the probe can be blocked or damaged by fly ash in the gas.

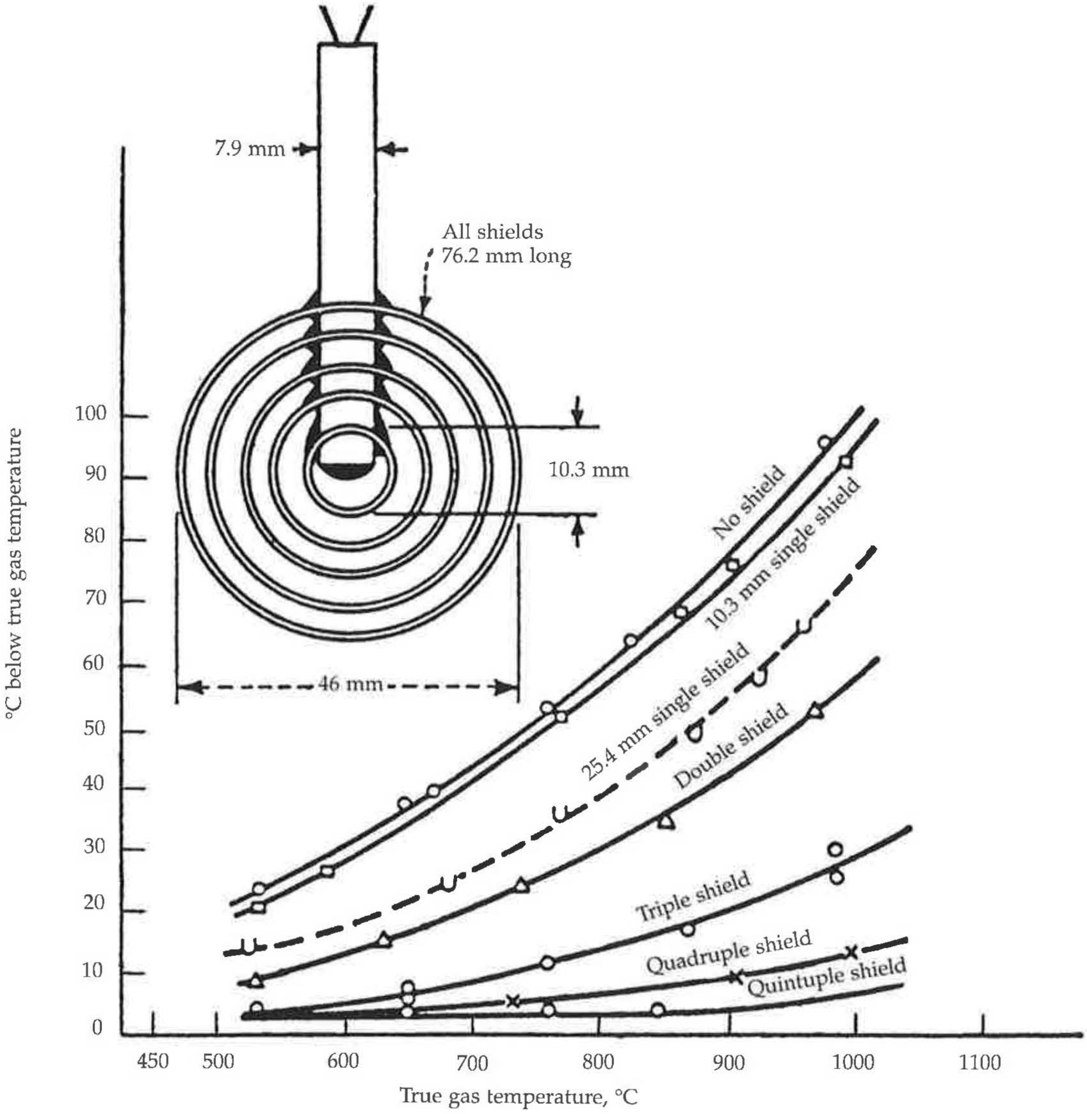

Figure 18 Reduction of heat losses from thermocouple using concentric shields (McAdams, 1954)

Conclusions

For accurate gas temperature measurement, the thermocouple should be small and mounted so as to minimize heat losses from the probe itself. Multiple thermocouples of different sizes, or radiation shields, are simple and effective means of increasing measurement accuracy.

EFFICIENCY OF COMBUSTION EQUIPMENT

Introduction

Measurements of the efficiencies of combustion systems indicate whether:

- a new system meets the specifications; or
- the performance of an existing system has deteriorated, which in turn would indicate that maintenance and/or adjustments to combustion controls are required.

The efficiencies of equipment such as boilers or process air heaters operating under steady conditions can be determined by one of the following two methods.

- *Direct or input/output method*
  Useful heat extracted in the combustion system is measured and expressed as a percentage of the heat supplied.

- *Indirect or loss method*
  Losses from the combustion system are determined as a percentage of the heat input. The efficiency of the system (as a percentage of the heat input) is one hundred minus the sum of all the losses.

Taking into account the accuracies attainable for various measurements, and their effects on the calculations of the efficiencies by the two methods, it can be shown that the indirect method is intrinsically more accurate (Fenton, 1977). Also, the measurements required for the direct method can often not be made – with desired accuracies – in an operating unit without costly modifications and disruption to the operations. The measurements needed for the indirect method do not suffer from this drawback. The indirect method also has the advantage of drawing attention to the various losses from the combustion system; it can therefore assist in controlling the efficiency of the equipment through minimization of the losses. The indirect method described in the following text is essentially similar to the methods described in the British Standards BS 845:Part 1: 1987.

Losses and data required

For determining efficiency of a combustion system by the indirect method, the following losses need to be evaluated:

(i) L_1– loss due to the sensible heat in the dry flue gas;

(ii) L_2– loss due to the water formed from combustion of the hydrogen in the fuel;

(iii) L_3– loss due to the moisture contained in the fuel;

(iv) L_4– loss due to the incomplete combustion of fuel resulting in carbon monoxide in the flue gas;

(v) L_5– loss due to the unburnt carbon in ash and grit;

(vi) L_6– loss due to the elevated temperature of ash when discharged from the combustion equipment;

(vii) L_7– loss due to the heat convected and radiated from the outer fabric of the combustion equipment.

In order to evaluate the above losses, the following data need to obtained at the time of the test.

(i) Ultimate analysis of fuel, on a dry, ash free basis for percentage mass of carbon, hydrogen and oxygen, C_C, C_H and C_O respectively.

(ii) Proximate analysis of fuel, on a wet basis, for moisture and ash content, C_m and C_a respectively.

(iii) Volumetric analysis of the dry flue gas for percentages V_{CO_2}, V_{O_2} and V_{CO} of CO_2, O_2 and CO respectively. The percentage of nitrogen, V_{N_2}, being found by balance:

$$V_{N_2} = 100 - (V_{CO_2} + V_{O_2} + V_{CO}) \qquad \textbf{(35)}$$

(iv) Unburnt carbon, U_c, expressed as a percentage of the mass of the ash collected during the test.

(v) Temperature of the ash leaving the combustion system, t_r, °C.

(vi) Temperature of the flue gas leaving the combustion system, t_g, °C. This temperature should be corrected for radiation loss as described earlier.

(vii) Temperature of the fuel and air entering the combustion system. This in most cases will be the ambient temperature, t_a, °C.

(viii) Gross calorific value, GCV, of fuel in kJ/kg on an as-fired basis. The gross calorific value on a dry ash free basis, can be adjusted to an as-fired basis by multiplying with $(1 - C_m/100 - C_a/100)$.

From the ultimate analysis of the fuel and moisture and ash contents, the composition of the fuel on an as-fired basis can be calculated as given below.

(i) C_m–moisture content on a wet basis as determined by proximate analysis.

(ii) C_a– ash content of fuel on a wet basis as determined by proximate analysis.

(iii) The carbon, hydrogen and oxygen contents, α_C, α_H and α_O respectively, as a percentage of the mass of the fuel as burnt can be calculated from the following:

$$\alpha_C = C_C \left(1 - \frac{C_m}{100} - \frac{C_a}{100}\right) \tag{36}$$

$$\alpha_H = C_H \left(1 - \frac{C_m}{100} - \frac{C_a}{100}\right) \tag{37}$$

$$\alpha_O = C_O \left(1 - \frac{C_m}{100} - \frac{C_a}{100}\right) \tag{38}$$

In biomass fuels, sulphur and nitrogen are present in such negligible quantities that their contributions need not be taken into account.

Calculation of losses and efficiency

The amount of unburnt carbon, as a percentage of the mass of the fuel, is calculated from the knowledge of the unburnt carbon in ash, U_C, in the ash collected during the test and ash content, C_a, of the fuel from the following:

$$\text{unburnt carbon} = \frac{U_C\ C_a}{100 - U_C} \tag{39}$$

Therefore the amount of carbon converted to CO_2, and CO, as a percentage of the mass of the fuel, is given by:

$$\text{carbon burnt} = \alpha_C - \frac{U_C\ C_a}{100 - U_C} \tag{40}$$

The next step is to determine the mass of dry flue gas, w_d, per unit mass of the fuel burnt. This is given by the following, from the mass of 100 kmol of dry flue gas, mass of carbon in 100 kmol of gas and the mass of carbon burnt per kg of fuel:

$$w_d = \frac{M_{CO_2} V_{CO_2} + M_{CO} V_{CO} + M_{O_2} V_{O_2} + M_{N_2} V_{N_2}}{M_C(V_{CO_2} + V_{CO})} \times \frac{1}{100} \left(\alpha_C - \frac{U_C\ C_a}{100 - U_C}\right) \tag{41}$$

Substituting values of the molar masses, the above equation simplifies to:

$$w_d = \frac{11\ V_{CO_2} + 8\ V_{O_2} + 7\ (V_{CO} + V_{N_2})}{3\ (V_{CO_2} + V_{CO})} \times \frac{1}{100}\ (\alpha_c - \frac{U_C\ C_a}{100 - U_C}) \tag{42}$$

Calculation of the loss L_1

Taking the mean heat capacity of the dry combustion products of biomass fuels – between 25 ° C and 400 °C and for air levels between stoichiometric and 300% excess – as 1.02 kJ/kg °C, the loss L_1 is given by:

$$L_1 = 1.02\ w_d\ (t_g - t_a\ )\ 100/GCV \tag{43}$$

Calculation of the loss L_2

Taking heat capacities of water vapour and liquid water as 1.97 and 4.19 kJ/kg °C respectively and heat of vaporization of water as 2257 kJ/kg (at 100 °C), the loss L_2 is given by:

$$L_2 = 9\alpha_H\{1.97(t_g - 100) + 2257 + 4.19(100 - t_a)\}/GCV \tag{44}$$

Calculation of the loss L_3

With the heat capacities of water vapour and liquid water and heat of vaporization of water as given above, the loss L_3 is given by:

$$L_3 = C_m\ \{1.97(t_g - 100) + 2257 + 4.19(100 - t_a)\}/GCV \tag{45}$$

Calculation of the loss L_4

The loss L_4 is calculated from the mass of carbon monoxide in the dry flue gas per unit mass of the fuel burnt, and taking the heat of combustion of carbon monoxide as 10100 kJ/kg (Rose and Cooper, 1977) this loss is given by:

$$L_4 = \frac{10100\ M_{CO}\ V_{CO}}{M_C(V_{CO_2} + V_{CO})} \times (\alpha_C - \frac{U_C\ C_a}{100 - U_C})/GCV \tag{46}$$

Substituting values of the molar masses, the above equation simplifies to:

$$L_4 = \frac{23567\ V_{CO}}{GCV\ (V_{CO_2} + V_{CO})} \times (\alpha_C - \frac{U_C\ C_a}{100 - U_C}) \tag{47}$$

Calculation of the loss L_5

Taking the heat of combustion of carbon as 33820 kJ/kg (BS 845: Part 1: 1987) the loss L_5 is given by:

$$L_5 = \frac{33820\ U_C\ C_a}{GCV\ (100 - U_C)} \tag{48}$$

Calculation of the loss L_6

The ash collected during the test consists of unburnt carbon and carbon free ash. The quantity of material collected per kg of fuel (as-fired basis) is given by:

$$(1 + \frac{U_C}{100 - U_C})\ \frac{C_a}{100} \tag{49}$$

Taking the average heat capacity of ash as 0.84 kJ/kg (Rose and Cooper, 1977), the loss L_6 is given by:

$$L_6 = (1 + \frac{U_C}{100 - U_C})\ 0.84\ C_a\ (t_r - t_a)/GCV \tag{50}$$

Fabric losses L_7

Fabric losses cannot be directly measured. There are some tabulated values of typical fabric losses from boiler plants in good order and operating at full rated values (BS 845:Part 1: 1987). These are given in Tables 8 and 9.

Table 8 Typical radiation, convection and conduction losses from water tube and shell boilers (BS 845: 1987)

Boiler type	Design detail	Total loss at rated output based on gross calorific value
1	Water-tube and multitubular shell boilers with rated output of 5 MW and above	0.3%
2	Water-tube and multitubular shell boilers with rated output of 2 MW and above but less than 5MW	0.5%
3	Water-tube and multitubular shell boilers with rated output of below 2 MW	1.0%
4	Brickset and dry back multitubular and brickhearth boilers	1.5%
5	Brickset water-tube boilers with water walls	2.0%
6	Brickset water-tube boilers without water walls	2.5%
7	Brickset Lancashire and Cornish boilers	4.0%

Radiation, convection and conduction losses are combined to give total loss as a percentage of heat input, under stable test conditions and at the rated output.

Table 9 Typical radiation, convection and conduction losses from sectional hot water boilers (BS 845: 1987)

Boiler type	Direct openings from combustion chamber	Water-cooled base	Closing and clean-out plastes and other non-water backed surfaces	Insulation	Total loss at rated output based on gross calorific value
A	None	Yes	Less than 10% of total surface	40 mm applied directly to boiler surface	1.5%
B	Less than 2000 mm^2/kW	No Temperature not exceeding 120 °C	Less than 10% of total surface	40 mm applied directly to boiler surface	3%
C	More than 2000 mm^2/kW	No Open botom not exceeding 9000 mm^2/kW	Less than 10% of total surface	25 mm within casing	4%

Radiation, convection and conduction losses are combined to give total loss as a percentage of heat input, under stable test conditions and at the rated output.

These losses can be estimated to a degree from calculations of the convected and radiated heat losses from exposed surfaces of the combustion equipment. The radiated heat, Q_r, from the equipment surface is calculated in kW from:

$$Q_r = \sigma \, \varepsilon_s \, A \, (T_s^4 - T_a^4) \tag{51}$$

Where σ is the Stefan-Boltzmann constant with a value of $5.67\text{x}10^{-11}$ kW/m^2 K^4, ε_s is the emissivity of the surface, A is the area of the surface in m^2, T_s and T_a are surface and ambient temperatures in kelvin. The emissivities of some surfaces are given in Table 10 (McAdams, 1954).

Table 10 Emissivities of common surfaces (McAdams, 1954).

Surface	Emissivity
Iron and steel	
polished steel	0.066
polished iron	0.14 – 0.38
iron plate, then rusted red	0.61
iron plate completely rusted	0.69
oxidized rolled sheet steel	0.66
mild steel with very thin layer of oxide	0.2–0.35
sheet steel with rough oxide layer	0.8–0.82
Stainless steel polished shiny surface	0.074
Painted surfaces	≈ 0.77 – 0.9
Aluminium paints	≈ 0.27 – 0.67
Bricks	
red	0.93
building	0.45
fireclay	0.75

The heat loss in kW, Q_c, by natural convection from surfaces is given by:

$$Q_c = h \, A \, (t_s - t_a) \tag{52}$$

where h is the heat transfer coefficient in kW/m^2 °C, t_s and t_a are the surface and ambient temperatures in °C, and A is the area of the surface. The heat transfer coefficients are correlated by equations of the form given below.

$$h = a \, \left(\frac{k_f}{L}\right) Ra_f^b \tag{53}$$

$$Ra_f = Gr_f \, Pr_f \tag{54}$$

$$Gr_f = \frac{L^3 \rho_f^2 \, g \, \beta_f \, (t_s - t_a)}{\mu_f^2} \tag{55}$$

where:

subscript f indicates that the properties are evaluated at film temperature $t_f = (t_s + t_a)/2$

Ra_f is the Raleigh number

Pr_f is Prandtl number for the air

Gr_f is Grashoff number

L is the characteristic dimension in m

ρ_f is density of air in kg/m^3

g is the acceleration due to gravity, equal to 9.81 m/s^2

β_f is the coefficient of cubical expansion for air and for the present case is given by $1/T_a$. T_a is the ambient temperature in K.
μ_f is the viscosity of air in N s/m^2
k_f is thermal conductivity of the air in kW/m °C.
the coefficient a and exponent b for various surfaces are given in Table 11.

The total heat loss, Q_t, from the surface of the combustion equipment is equal to the sum of the convected and radiated heat losses:

$$Q_t = Q_c + Q_r \tag{56}$$

This loss must be expressed as a percentage of the gross calorific value of the fuel as-fired. If fuel usage rate is given by R_{fu} kg/s then the loss L_7 will be given by:

$$L_7 = \frac{100\ Q_t}{R_{fu}\ GCV} \tag{57}$$

Table 11 Coefficients and exponents for equation (53) (McAdams, 1954)

a	b	Surface type	Characteristic dimension L	Raleigh number Ra range
0.13	0.33	Vertical plates and cylinders	Vertical height of plate or cylinder	10^9–10^{12}
0.59	0.25	Vertical plates and cylinders	Vertical height of plate or cylinder	10^4–10^9
0.53	0.25	Horizontal cylinders	Cylinder diameter	10^3–10^9
0.14	0.33	Horizontal plates, heated plate facing upwards or cooled plate facing upwards or cooled plate facing downwards	Plate length	2×10^7–3×10^{10}
0.54	0.25	Horizontal plates, heated plate facing upwards or cooled plate facing downwards	Plate length	10^5–2×10^7
0.27	0.25	Horizontal plates, heated plate facing downwards or cooled plate facing upwards	Plate length	3×10^5–3×10^{10}

Efficiency

The efficiency, E, as a percentage of the heat input into the combustion system is then given by:

$$E = 100 - (L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7) \tag{58}$$

For many properly maintained systems of good design, quantities of unburnt carbon and carbon monoxide are small, and heat losses are dominated by the losses L_1, L_2 and L_3 and fabric loss L_7. In these cases the losses in the flue gases can be approximated by assuming complete combustion, and flue gas losses can then be determined from measurements of moisture content of the fuel, temperature and concentration of either carbon dioxide or oxygen in the dry flue gas. For complete combustion, dry flue gas concentrations are related by:

$$V_{CO_2} = (1 - \frac{V_{O_2}}{21})\ V_{CO_2,s} \tag{59}$$

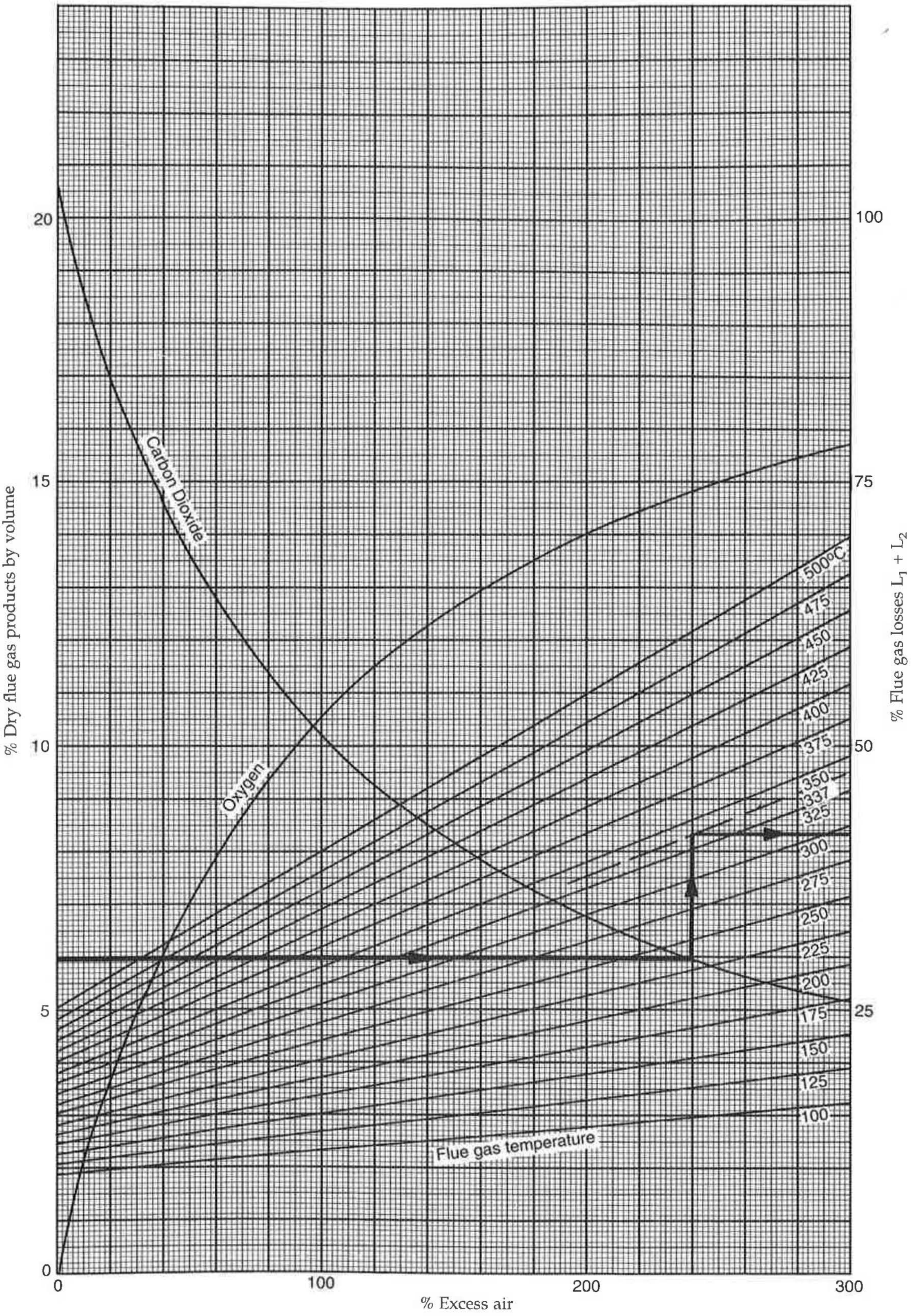

Figure 19 Sum of flue gas losses L_1 and L_2 (Breag *et al.*, 1992)

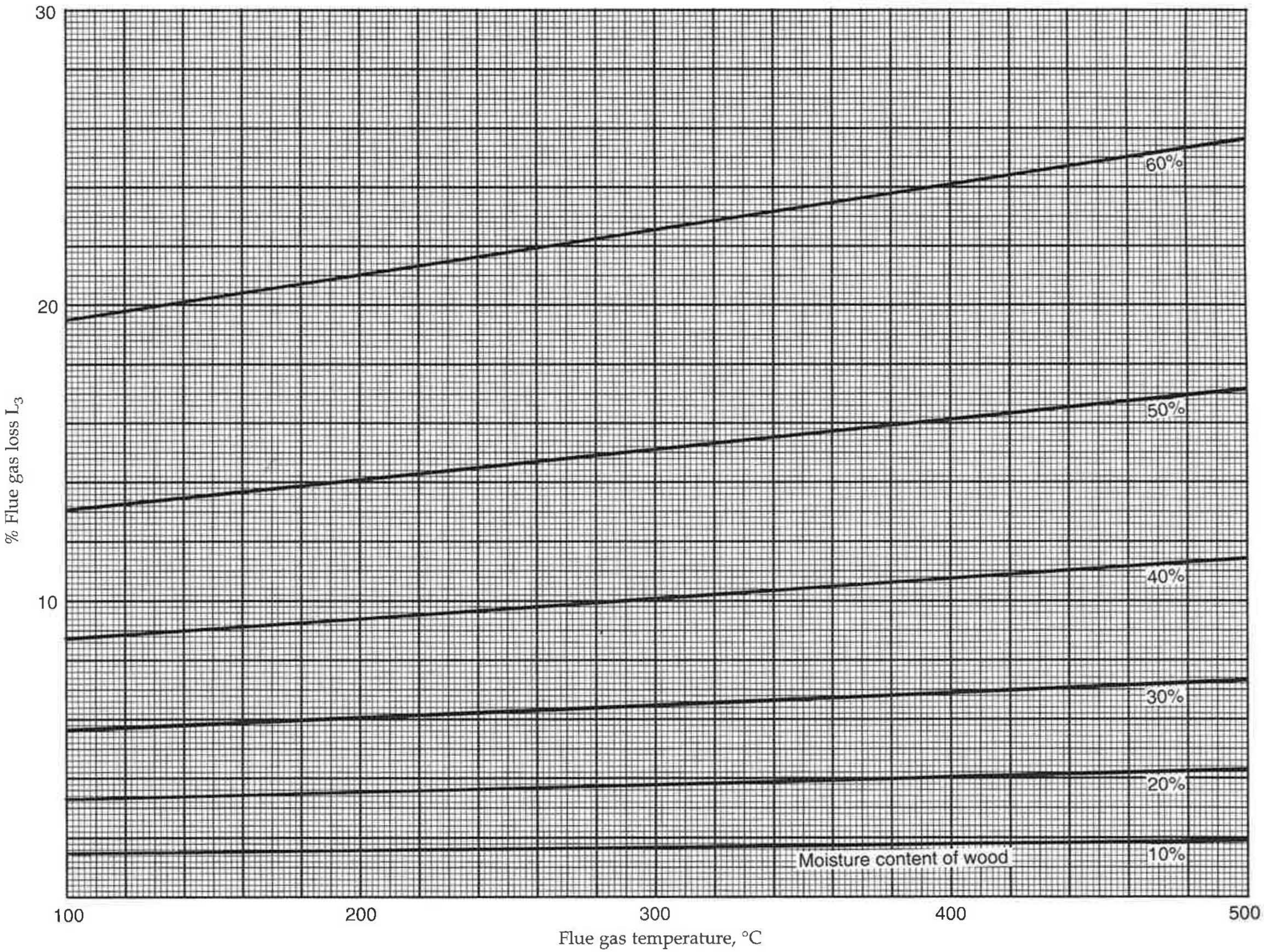

Figure 20 Flue gas loss L_3 (Breag *et al.*, 1992)

Where $V_{CO_2,s}$ is the concentration of CO_2 in dry flue gas calculated for stoichiometric fuel and air mixture. For typical woody biomass this is equal to 20.5%. The losses L_1, L_2 and L_3 were calculated for typical woody biomass (assuming complete combustion) and presented in a graphical form in a companion publication (Breag *et al.*, 1992). These graphs are reproduced in Figures 19 and 20. For measured concentration of either oxygen or carbon dioxide from the scale for the concentration, in Figure 19, draw a horizontal line until it meets the curve for either carbon dioxide or oxygen as the case may be. From this point on the concentration curve draw a vertical line until the isotherm for the measured flue gas temperature is reached. From this point on the isotherm extend a horizontal line to the loss scale on the graph. The loss indicated is equal to the sum of L_1 and L_2. The loss L_3 is read from Figure 20 for appropriate moisture content of the fuel and temperature of the flue gas. If the ash contains large quantities of unburnt carbon the procedures given in equations (35)–(57) would be more appropriate than this graphical method.

Operational considerations

Regular checks on the system efficiency will assist in planning maintenance schedules and will help in avoiding increased fuel costs due to the loss in the efficiency of the equipment. If, as a result of the calculations described above, the efficiency of the equipment is found to be low, then adjustment of the controls for combustion air and/or maintenance is indicated. The air levels should not be adjusted to such low values that excessive amounts of unburnt carbon or carbon monoxide are generated, or temperatures in the combustion unit exceed the design limits of the equipment.

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APPENDIX Tables

Table A1 Bulk density of biomass materials

	Bulk density* kg/m³	Moisture content %	Reference
Wood and wood residues			
Acacia wood, chopped	170	NQ	5
Bark, crushed	160–321	NQ	1
Beech logs	400	NQ	8
Beech logs	420	10	8
Beech logs	450	20	8
Beech logs	480	30	8
Beech logs	510	40	8
Beech logs	530	50	8
Beech wood chips	180	10	8
Beech wood chips	220	30	8
Beech wood chips	200	20	8
Beech wood chips	235	40	8
Meranti wood chips	160	NQ	5
Pine wood chips	152	NQ	5
Planer shavings	96	NQ	11
Rubber wood chips	140	NQ	5
Sawdust	100–150	NQ	3
Sawdust	160	NQ	11
Softwood chips	176–192	DRY	6
Spruce logs	310	NQ	8
Spruce logs	330	10	8
Spruce logs	350	20	8
Spruce logs	370	30	8
Spruce logs	390	40	8
Spruce logs	410	50	8
Spruce wood chips	160	10	8
Spruce wood chips	180	20	8
Spruce wood chips	200	30	8
Spruce wood chips	240	40	8
Wood, pelleted	560–608	NQ	11; 6
Hardwood chips	224	NQ	6
Wood chips	160–481	NQ	1
Agricultural residues			
Bagasse	112–160	NQ	12
Coconut coir	45	NQ	3
Coconut shells, chopped	330	NQ	5
Corn stalks, bales	100	10	8
Flax stive, bales	140	10	8
Palm oil shells	442	NQ	5
Rice husks	100	NQ	3
Rice husks, briquettes	680	NQ	3
Rice straw, LP Size 10mm	63–121	13	10
Rice straw, LP Size 17mm	46–111	13	10
Rice straw, LP Size 70mm	33–64	13	10
Rice straw, LP Size 170mm	11–17	13	10
Rice straw, big roll bale	96–112	DRY	10
Straw bales stored,			
inside buildings	160–214	NQ	7
in the field	107–128	NQ	7
Straw, bales	60–160	NQ	8

	Bulk density* kg/m^3	Moisture content %	Reference
Agricultural residues (contd.)			
Straw, chopped	40–60	NQ	8
Straw, baled	68–80	DRY	9
Straw, baled	110–200	NQ	4
Straw, briquettes	300–600	NQ	8
Straw, chopped	64–80	DRY	7
Straw, chopped	92–128	DRY	9
Straw, chopped	40–80	DRY	4
Straw, briquettes	320–640	DRY	4
Straw, hammer-milled	40–100	DRY	2
Straw, loose	80	NQ	3
Straw, loose	20–40	NQ	4
Straw, LP	59–64	DRY	7
Straw, LP	32–48	DRY	9
Straw, pelleted	560–720	NQ	4
Wheat stalk, big bale	66–111	DRY	10
Wheat stalk, small bale	44–67	DRY	10

References:
1 Anon., 1984
2 Ebeling *et al.*, 1985; Arthur *et al.*, 1982
3 Kaupp *et al.*, 1985
4 Knutson *et al.*, 1982
5 Maniatis, 1988
6 Miles, 1984
7 Richey *et al.*, 1961
8 Strehler, 1988
9 Structures and Environment Handbook, 1977
10 Susawa *et al.*, 1981; 1985
11 Technology Application Lab, 1984
12 Susawa, 1989

Notes:
* With logs a more common term for bulk density is stacking density
LP Loosely piled
NQNot quoted

Table A2 Moisture content of biomass materials

	Moisture content %	Condition	Reference
Wood			
Acacia mearnsii	39	Green	5
Alder	50	Green	8
Apple	43	Green	8
Ash	27	Green	8
Aspen	44	Green	8
Beech	39	Green	8
Beech	30–60	NQ	1
Birch	47	Green	8
Birch chips	36	Green	4
Black poplar	52	Green	8
Bole wood	35–60	NQ	3
Cull material	40–70	NQ	8
Douglas fir	30–60	NQ	1
Douglas fir, bark	25–75	NQ	1
Elm	34	Green	8
Eucalyptus grandis	47	Green	5
Eucalyptus paniculata	28	Green	5
Eucalyptus saligna	45	Green	5
European larch chips	45	Green	4
Hog fuel	30–60	NQ	10
Hornbeam	37	Green	8
Horse-chestnut	48	Green	8
Italian poplar	48	Green	8
Larch	50	Green	8
Lime	52	Green	8
Lodgepole pine	51	Air-dried	4
Maple	39	Green	8
Mixed softwood	25	Air-dried	4
Mixed softwood	31	Air-dried	4
Mixed softwood	35	Air-dried	4
Mixed softwood	37	Air-dried	4
Mixed softwood chips	31	Air-dried	4
Mixed softwood chips	36	Air-dried	4
Mixed softwood chips	39	Air-dried	4
Mixed softwood chips	41	Air-dried	4
Mixed softwood chips	43	Air-dried	4
Mixed softwood chips	46	Air-dried	4
Mixed softwood chips	53	NQ	4
Mixed softwood chips	54	NQ	4
Mountain ash	28	Green	8
Oak	35	Green	8
Oak chips	42	Green	4
Pinus patula	56	Green	5
Planer shavings	8–19	NQ	9
Plum	34	Green	8
Red fir	45	Green	8
Robinia	29	Green	8
Sallow	42	Green	8
Sawdust	25–40	NQ	1
Sawdust	25–55	NQ	9
Sawdust	40–55	NQ	10
Scotch pine	61	Green	8
Silver fir	37	Green	8
Sitca spruce chips	52	Air-dried	4

	Moisture content %	Condition	Reference
Wood (contd.)			
Sitca spruce chips	56	Green	4
Spruce	56	Green	8
Top wood	35–60	NQ	6
Tree prunings	35–55	Green	7
White willow	51	Green	8
Willow chips	50	Green	4
Wood	45–65	Green	2
Wood bark	30–60	NQ	10
Wood chips	40–50	NQ	10
Wood shavings	16–40	NQ	1
Agricultural residues			
Bagasse	40–60	NQ	12
Barley straw	12–22	NQ	12
Coconut shells	10–20	NQ	12
Coffee hulls	65–75	Green	2
Corn cobs	25–45	NQ	11
Corn stalks	40–60	NQ	7
Cotton gin trash	7–12	NQ	10
Cotton stalks	35–45	Green	2
Cotton stalks	40–50	NQ	7
Maize straw	50–70	NQ	12
Peach pits	30–40	NQ	10
Rice husks	7–10	NQ	10
Rice straw	50–80	NQ	7
Rice straw	12–22	NQ	12
Straw	16–20	NQ	1
Straw	30–40	Green	2
Wheat straw	8–20	NQ	7
Wheat straw	12–22	NQ	12

References:
1 Bridgewater, 1991
2 Buekens *et al.*, 1990
3 Cheremisinoff, 1980; Hiser, 1977
4 ETSU, 1990
5 Gore, 1982
6 Hiser, 1977
7 Jenkins *et al.*, 1989
8 Klar *et al.*, 1925
9 Knutson *et al.*, 1982
10 Rossi, 1984
11 Schertz *et al.*, 1984
12 Strehler *et al.*, 1987

Notes: NQ Not quoted

Table A3 Proximate and ultimate analysis of biomass materials

Proximate analysis
  Volatile matter content on dry basis as % mass
  Fixed carbon on dry basis as % mass
  Ash content on dry basis as % mass
Ultimate analysis
  Carbon content on dry ash free basis as % mass
  Hydrogen content on dry ash free basis as % mass
  Oxygen content on dry ash free basis as % mass
  Nitrogen content on dry ash free basis as % mass
  Sulphur content on dry ash free basis as % mass
  Gross calorific value on dry ash free basis as MJ/kg

	Volatile matter %	Fixed carbon %	Ash content %	Carbon content %	Hydrogen content %	Oxygen content %	Nitrogen content %	Sulphur content %	Gross calorific value MJ/kg	Reference
Wood										
Acacia erubesens, heartwood				52.32	6.17	41.22	0.28			16
Acacia erubesens, sapwood				47.93	6.33	45.52	0.22		19.23	16
Acacia karroo, sapwood				47.50	6.47	45.60	0.43		19.64	16
Acacia pinnata									18.6	2
Acacia spp.	79.87	18.16	1.96	49.80	5.20	44.70	0.30		17.97	9
Acacia tortilis, sapwood				48.16	6.41	45.05	0.37		19.43	16
Albizia chinensis									18.7	2
Albizia procera									18.7	2
Bauhinia variegata									19.0	2
Beech				51.91	6.34	41.75			20.42	10
Berberis aristata									19.4	2
Big leaf maple	87.90	11.50	0.60	50.18	6.13	43.52	0.14	0.03		14
Birch chips	83.85	14.75	1.40	50.90	7.60	40.50	0.50	0.50	20.29	6
Black locust	80.94	18.26	0.80	51.23	5.76	42.34	0.58	0.01	19.90	8
Black oak	85.60	13.00	1.40	49.64	6.12	44.07	0.15	0.02	18.91	8
Black walnut	80.69	18.53	0.78	50.23	5.87	43.62	0.22	0.01	19.99	8
Brassica sp.	79.54	16.78	3.68	42.90	6.10	47.60	1.30			9
Canyon, live oak	88.20	11.30	0.50	48.09	5.83	46.00	0.07	0.01	19.08	14
Carissa spinarum									18.7	2
Casuarina	78.94	19.66	1.40	49.32	5.91	43.99	0.60	0.02	19.72	8

	Volatile matter %	Fixed carbon %	Ash content %	Carbon content %	Hydrogen content %	Oxygen content %	Nitrogen content %	Sulphur content %	Gross calorific value MJ/kg	Reference
Wood (contd)										
Cattails	71.57	20.53	7.90	46.80	5.71	46.23	0.81	0.04	19.39	8
Cedar	77.00	21.00	2.00							13
Cedar, western red	86.50	13.20	0.30							14
Chaparral	75.19	18.68	6.13	50.57	5.48	43.31	0.58	0.03	20.07	8
Chinkapin	86.90	12.80	0.30	49.82	5.95	44.15	0.07	0.01	19.41	14
Citrus aurantium									21.0	2
Colophospermum mopan, heartwood				55.86	6.28	37.59	0.28		21.57	16
Colophospermum mopan, sapwood				50.00	6.41	43.25	0.34			16
Combretum erythrophy				44.16	5.91	49.58	0.35		16.67	16
Combretum imberbe				51.40	5.84	42.54	0.22		19.79	16
Cotinus coggygria									19.3	2
Cotoneaster affinis									19.7	2
Daphniphyllum himalense									20.2	2
Debregeasia salicifolia									18.4	2
Douglas fir				52.70	6.40	40.80	0.10		21.22	13
Douglas fir				52.72	6.35	40.83	0.10			4
Douglas fir	86.20	13.70	0.10							7
Douglas fir	87.30	12.60	0.10	50.69	6.19	43.04	0.06	0.02	20.39	14
Engelhardintia spicata									17.8	2
English walnut	80.82	18.10	1.08	50.26	5.69	43.61	0.37	0.01	19.84	8
Eucalyptus	80.40	17.73	0.99	49.00	5.90	44.80	0.30		17.68	9
Eucalyptus camaldule, sapwood				48.90	6.33	44.44	0.33		19.88	16
Eucalyptus camaldulensis	81.42	17.82	0.76	49.36	5.91	44.29	0.30	0.01	19.56	8
Eucalyptus globulus	81.60	17.30	1.10	48.73	5.98	44.68	0.39	0.01	19.44	8
Eucalyptus grandis	82.55	16.93	0.52	48.53	5.91	45.32	0.15	0.01	19.43	8
Eucalyptus, leaves	77.78	17.39	4.83							18
European larch, chips	91.52	7.76	0.72	50.90	6.40	42.70			17.65	6
Eurya acuminata									20.1	2
Ficus gibbosa									20.1	2
Ficus lacor									18.9	2

	Volatile matter %	Fixed carbon %	Ash content %	Carbon content %	Hydrogen content %	Oxygen content %	Nitrogen content %	Sulphur content %	Gross calorific value MJ/kg	Reference
Wood (contd)										
Ficus oligodon									18.6	2
Ficus semicordata									19.2	2
Hemlock	84.80	15.00	0.20							13
Hickory				50.05	6.55	43.40			20.24	10
Lennea coromandelica									19.3	2
Leucaena	80.94	17.53	1.53	49.95	6.14	43.39	0.48	0.03	19.36	5
Lvonia ovolifolia									19.3	2
Machilus odaratissima									19.8	2
Madrone	82.99	16.44	0.57	48.48	6.02	45.41	0.06	0.02	19.61	8
Madrone	84.50	15.10	0.30	48.68	6.60	45.19	0.05	0.02	19.19	14
Manzanita	81.29	17.89	0.82	48.67	6.00	45.13	0.17	0.02	19.49	8
Maple				51.32	6.09	42.29	0.30		20.18	10
Mixed softwood, air dried	77.38	18.00	4.77	51.20	6.30	42.40	0.10		19.14	6
Mixed softwood, air dried	80.00	18.13	1.87	52.10	8.10	39.10	0.30	0.40	20.40	6
Murraya koenigii									18.4	2
Oak				50.50	5.80	41.60	0.00	0.00	19.88	3
Oak chips	80.52	16.72	2.76	50.40	8.90	39.70	0.50	0.50	19.71	6
Pine, air dried	60.61	34.90	4.69	53.60	6.20	40.10	0.10		19.30	6
Pitch pine				59.70	7.30	33.00			24.49	13
Ponderosa pine	82.54	17.17	0.29	49.40	6.01	44.49	0.06	0.03	20.08	8
Ponderosa pine	87.00	12.80	0.20							7
Poplar				51.90	6.30	41.80			19.21	13
Poplar				51.91	6.34	41.75			20.82	10
Poplar	82.32	16.35	1.33	49.15	5.93	44.32	0.48	0.01	19.66	8
Premna barbata									20.87	2
Princepia utilis									19.1	2
Prunus persica									20.75	2
Prunus venosa									19.9	2
Pyracantha crenulata									19.7	2
Red alder	87.10	12.50	0.40	49.75	6.08	43.96	0.13	0.07	19.38	14

	Volatile matter %	Fixed carbon %	Ash content %	Carbon content %	Hydrogen content %	Oxygen content %	Nitrogen content %	Sulphur content %	Gross calorific value MJ/kg	Reference
Wood (contd)										
Redwood				53.60	5.90	40.40	0.10		21.07	13
Redwood	79.72	19.92	0.36	50.85	6.00	43.05	0.05	0.03	20.79	8
Redwood	83.50	16.10	0.40	53.61	5.91	40.38	0.10		21.04	17
Redwood, heartwood	80.28	19.55	0.17							8
Redwood, sapwood	80.12	19.21	0.67							8
Rhus perviflora									18.3	2
Rhus punjabensis									18.9	2
Salix tetrasperma									19.3	2
Saurauja nepaulensis									18.1	2
Sitca spruce chips	80.68	17.05	2.27	50.50	6.20	43.20	0.10		17.99	6
Sitca spruce chips	83.78	14.55	2.07	50.00	5.90	43.90	0.20		19.73	6
Softwood, air dried	62.52	34.29	3.19	54.90	6.90	38.00	0.20		18.17	6
Symplocos paniculatus									18.6	2
Tan oak	87.10	12.40	0.50	48.58	6.15	45.12	0.03	0.03	19.22	14
Tan oak, mixed	80.93	17.40	1.67	48.79	6.05	45.02	0.12	0.01	18.06	8
Tan oak, sapwood	83.61	15.36	1.03							8
Toona serrata									19.8	2
Viburnum cylindricum									18.9	2
Western hemlock				51.50	5.90	42.40	0.10	0.10	20.50	13
Western hemlock	84.80	15.00	0.20	51.53	5.93	42.33	0.10	0.10	20.45	17
Western hemlock	87.00	12.70	0.30						19.95	14
Western red cedar	86.50	13.20	0.30						20.62	14
White ash				50.00	6.90	43.10			19.15	13
White cedar				49.00	6.40	44.60			18.05	13
White fir	83.17	16.58	0.25	49.10	5.99	44.84	0.05	0.01	19.99	8
White fir	84.40	15.10	0.50							13
White oak				50.50	6.60	42.80			18.89	13
White oak	81.28	17.20	1.52	50.29	5.47	43.83	0.36	0.01	19.74	8
Willow chips	83.36	15.04	1.59	51.00	6.00	42.90	0.10		18.73	6
Ziziphus mucronata				42.40	5.52	51.62	0.46		16.19	16

	Volatile matter %	Fixed carbon %	Ash content %	Carbon content %	Hydrogen content %	Oxygen content %	Nitrogen content %	Sulphur content %	Gross calorific value MJ/kg	Reference
Wood bark and mill-waste										
Acacia erubesens				48.85	6.38	42.76	2.01			16
Acacia karroo				49.62	6.31	42.78	1.29			16
Acacia tortilis				52.98	6.64	38.25	2.13			16
Alabama oak, chips	74.70	21.90	3.30							3
Alder	74.30	23.30	2.40							13
Black oak	81.00	16.90	2.10						17.46	14
Cedar	86.70	13.10	0.20							13
Cedar western, red	77.60	21.20	1.20						21.09	14
Chinkapin	80.50	19.30	0.20						22.44	14
Colophospermum mopan				52.51	6.44	40.32	0.73			16
Combretum erythrophy				39.36	5.05	54.52	1.07			16
Cottonwood	79.50	17.50	3.00							14
Douglas fir	70.60	27.20	2.20	56.88	5.97	37.15	0.00		22.26	17
Douglas fir	73.00	25.80	1.20							13
Douglas fir	73.60	25.90	0.50						22.04	14
Eucalyptus camaldule				45.26	5.60	48.74	0.40			16
Jack pine waste	74.33	23.67	2.17	53.40	5.90	38.60	0.10		20.76	12
Oak				41.50	5.70	52.50	0.20	0.10	20.56	1
Pine				53.86	5.97	39.96	0.21		21.00	10
Pine	73.00	24.20	3.00	55.00	5.80	39.00	0.10	0.10	21.63	12
Ponderosa pine	73.40	25.90	0.70							7
Red alder	77.30	19.70	3.00						20.04	14
Redwood				52.10	5.10	42.60	0.10	0.10	19.49	1
Redwood	71.30	27.90	0.80							7
Redwood, mill waste	81.19	18.63	0.18							8
Redwood, shavings	74.70	21.90	3.30							3
Sitca spruce, air dried residues	79.61	16.55	3.84	50.10	5.90	43.80	0.20		19.36	6
Tan oak	73.11	23.40	3.49							8
Tan Oak	76.30	20.80	2.90						19.92	14

	Volatile matter %	Fixed carbon %	Ash content %	Carbon content %	Hydrogen content %	Oxygen content %	Nitrogen content %	Sulphur content %	Gross calorific value MJ/kg	Reference
Wood bark and mill-waste (contd)										
Western hemlock	73.90	24.30	0.80						22.16	14
Western hemlock	74.30	24.00	1.70							7
Western red cedar	77.60	21.20	1.20						21.09	14
White fir	73.40	24.00	2.60							7
Ziziphus mucronata				41.09	5.04	52.93	0.94			16
Agricultural residues										
Almond shells	73.45	21.74	4.81	47.65	6.32	44.77	1.23	0.02	20.36	8
Almond shells				52.52	6.15	41.00	0.24	0.10		14
Babassu husks	79.71	18.70	1.59	51.19	5.46	43.03	0.26	0.04	20.24	8
Bagasse				48.86	6.35	44.38	0.31	0.10	18.73	15
Bagasse, sugar cane	73.78	14.95	11.27	49.67	5.93	43.84	0.42	0.01	19.21	8
Bagasse, sugar cane	84.22	12.00	3.78	47.70	5.90	44.60	1.80		18.95	12
Bagasse, sweet sorghum	75.65	18.48	5.87	51.00	5.60	41.50	1.80	0.10	18.92	12
Barley straw	68.80	20.90	10.30	44.23	5.84	48.54	1.39		19.30	8
Barley straw				50.40	6.79	42.22	0.47	0.12	16.82	15
Cocoa hulls	67.95	23.80	8.25	53.74	5.83	36.98	3.32	0.13	20.75	8
Coconut fibre dust	66.58	29.70	3.72	52.46	5.27	41.34	0.47	0.16	20.82	8
Coconut shells	81.80	17.60	0.60						20.68	14
Coconut shells				51.99	5.80	41.75	0.36	0.10	19.45	15
Corn cobs	80.10	18.54	1.36	47.24	5.95	46.11	0.48	0.01	19.30	8
Corn stover	75.17	19.25	5.58	46.56	5.93	46.20	0.65	0.01	18.83	8
Cotton gin trash	67.30	15.10	17.60	47.52	6.31	43.66	2.47		19.71	8
Cotton gin trash	82.16	8.47	9.36	54.10	8.20	35.70	1.60	0.40	17.95	12
Cotton gin trash	75.40	15.40	9.20	50.13	5.95	41.47	1.79	0.64	18.26	14
Cotton seed husks	76.08	21.37	2.55	49.90	6.30	42.70	1.00	0.10	19.38	12
Cotton stalks	68.88	26.56	4.56	53.60	5.20	38.90	1.30	1.00	18.11	12
Cotton stalks	73.29	21.20	5.51	50.00	5.68	43.32	0.69	0.21	19.32	18
Jute sticks	92.55	6.55	0.90	49.49	6.75	40.56	2.95	0.25	19.52	11
Maize straw				50.44	5.93	42.62	0.87	0.13	17.83	15

	Volatile matter %	Fixed carbon %	Ash content %	Carbon content %	Hydrogen content %	Oxygen content %	Nitrogen content %	Sulphur content %	Gross calorific value MJ/kg	Reference
Agricultural residues (contd)										
Peanut hulls	73.02	21.09	5.89	49.46	5.90	42.75	1.76	0.13	19.81	8
Peanut shells	71.60	22.20	6.20						18.70	14
Rice husks				45.56	6.75	47.10	0.59			4
Rice husks	65.47	16.67	17.86	50.16	5.26	43.91	0.49	0.02	19.64	8
Rice husks	38.80	37.83	23.37	49.40	6.20	43.80	0.30	0.40	17.37	12
Rice husks	63.60	15.80	20.60	48.48	5.52	44.87	1.05	0.08	18.75	14
Rice straw				48.51	6.31	44.31	0.74	0.12	19.55	10
Rice straw				47.51	5.78	45.79	0.77	0.15	17.67	15
Rice straw, fresh	69.33	17.25	13.42	49.68	5.51	43.48	0.83	0.10	18.80	8
Rice straw, weathered	62.31	13.33	24.36	46.14	5.24	47.17	1.24	0.21	19.25	8
Straw				50.47	6.19	42.18	1.05	0.10		4
Sunflower seed husks	73.85	21.90	4.25	51.10	6.30	41.50	0.90	0.20	20.87	12
Wheat straw	71.30	19.80	8.90	48.76	5.64	44.47	0.69	0.12	19.76	8
Wheat straw				51.92	5.92	41.81	0.30	0.05	18.51	15

References: 1 Anon., 1978
2 Bhatt *et al.*, 1990
3 Boley *et al.*, 1969
4 Bridgewater, 1991
5 Duncan *et al.*, 1981
6 ETSU, 1990
7 Howlett *et al.*, 1977
8 Jenkins *et al.*, 1985
9 Kandpal *et al.*, 1993
10 Kaupp *et al.*, 1985; Llewellen *et al.*, 1977
11 Kumar *et al.*, 1984
12 Magasiner *et al.*, 1987
13 Pingrey, 1976
14 Rossi, 1984
15 Strehler *et al.*, 1987
16 Tietema *et al.*, 1991
17 Tillman, 1978
18 Univeristy of California, 1986

Table A4 Fusion temperatures and chemical composition of ash from some biomass materials

Fusion temperatures	Atmosphere	IDT °C	ST °C	HT °C	FT °C	Reference
Wood and wood bark						
Birch	Reducing	1365			1380	3
Birch	NQ	1488	1493		1499	5
Eastern hemlock	NQ	1516	1521		1427	5
Jack pine	NQ	1343	1510		1516	5
Jack pine waste	NQ	1343		1400	1400	4
Madrone wood	Oxidizing	1271	1330	1352	1404	8
Manzanita wood	Inert(N_2)	1080			1400	6
Maple	NQ	1454	1549		1554	5
Oak	Reducing	1360			1380	3
Softwood	Reducing	1170		1180	1200	3
Tan oak	Oxidizing	1390	1440	1449	1457	8
Tan oak	Reducing	1377	1438	1446	1454	8
Wood	Reducing	1450–1515			1500–1550	2
Oak bark	Reducing	1477	1493		1504	1
Oak bark	Oxidizing	1471	1499		1510	1
Pine bark	Reducing	1193	1226		1266	1
Pine bark	Oxidizing	1210	1249		1288	1
Pine bark	NQ	1193		1277	1266	4
Agricultural residues						
Alfalfa seed straw	Inert(N_2)	700		1550		6
Almond shell	Inert(N_2)	790		1440		6
Bagasse, sweet sorghum	NQ	1236		1244	1252	4
Barley straw	Inert(N_2)	925			1100	6
Corn cobs	Inert(N_2)	900			1020	6
Corn stalks	Inert(N_2)	820			1091	6
Cotton gin trash	Inert(N_2)	1010			1380	6
Cotton seed husks	NQ	1390		1400	1400	4
Rice husks	NQ	1400		1400	1400	4
Rice husks	Inert(N_2)	1439			1650	6
Rice straw	Inert(N_2)	1060			1250	6
Rice straw	Oxidizing	1027	1421	1421	1500	7
Rice straw	Reducing	1027	1438	1410	1500	7
Sunflower seed husks	NQ	940		980	1020	4
Vineyard prunings	Reducing	1213	1216	1221	1227	8
Vineyard prunings	Oxidizing	1216	1218	1224	1229	8
Walnut shells	Inert(N_2)	820			1225	6

References:
1 Anon., 1972
2 Baumeister *et al.*, 1978
3 ETSU, 1990
4 Magasiner *et al.*, 1987
5 Mingle *et al.*, 1968
6 Osman *et al.*, 1983
7 Pittsburgh lab., 1976
8 Rossi, 1984

Notes:
IDT Initial deformation temperature
HT Hemispherical temperature
NQ Not quoted
ST Softening temperature
FT Flow temperature

Table A5 Chemical compositions of ash from some biomass materials

	SiO_2 %	Fe_2O_3 %	TiO_3 %	Al_2O_3 %	Mn_3O_4 %	CaO %	MgO %	Na_2O %	K_2O %	SO_3 %	Cl %	P_2O_5 %	MnO %	Unaccounted %	Reference
Wood and wood bark															
Birch	2.8	0.7	0.1	1.4		45.0	10.8	1.3	11.4	2.2		17.0	5.6	1.7	2
Jack pine waste	16.0	5.0		6.3		51.6	5.5		4.1						5
Oak	2.3	0.5	0.1	0.9		65.0	8.3			2.2		7.5	0.9	1.6	2
Oak bark	11.1	3.3	0.1	0.1		64.5	1.2	8.9	0.2	2.0					1
Pine bark	39.0	3.0		14.0		25.5	6.5	1.3	6.0						5
Pine bark	39.0	3.0	0.2	14.0		25.5	6.5	1.3	6.0	0.3					1
Redwood bark	14.3	3.5	0.3	4.0	0.1	6.0	6.6	18.0	10.6	7.4	18.4				1
Softwood	36.3	1.5	0.3	4.7		32.0	4.4	2.3	8.5	1.7		4.8	1.8	1.7	2
Spruce bark	32.0	6.4	0.8	11.0	1.5	25.3	4.1	8.0	2.4	2.1					1
Wood	0.1–50	.05–3				10–60	1–17	<10	1–40						3
Agricultural residues															
Bagasse, sugar cane	62.6	2.4		3.3		4.5		2.8	2.9						5
Bagasse, sweet sorghum	56.6	2.2		3.6		8.9		1.4	5.0						5
Cotton gin trash	40.7	3.3		4.3		16.1	8.0		11.3						5
Cotton seed husks	0.4	0.9		0.6		7.8	12.1	1.4	42.0						5
Cotton stalks	8.4	0.5		0.8		16.4	5.2	2.0	30.0						5
Corn stover	19.0	1.5				14.0	3.0	13.0	27.0						3
Rice husks	95.6	0.1		2.0		0.2	0.2	0.1	1.2						5
Rice husks	95.0	0.5				1.0	1.0	1.0	1.0						3
Rice straw	56.0	0.5				6.0	2.0	6.0	15.0						3 & 4
Sunflower seed husk	1.7	0.6		0.1		9.2	7.2	0.4	39.3						5
Wheat straw	56.0	0.5				6.0	2.0	6.0	15.0						3

References

1 Anon., 1978
2 ETSU, 1990
3 Kaupp *et al.*, 1985
4 Llewellen *et al.*, 1977
5 Magasiner *et al.*, 1987

Table A6 Formulae for calculation of results to different bases

Property basis given	Property basis wanted		
	As-fired or wet	Dry	Dry ash free
As-fired or wet		$\frac{100}{100 - C_m}$ *or* $\frac{100 + C_{md}}{100}$	$\frac{100}{100 - (C_m + C_a)}$
Dry	$\frac{100 - C_m}{100}$ *or* $\frac{100}{100 + C_{md}}$		$\frac{100}{100 - C_{ad}}$
Dry, ash free	$\frac{100 - (C_m + C_a)}{100}$	$\frac{100 - C_{ad}}{100}$	

Notes: To convert a value to a different basis, the value should be multiplied by the appropriate formula shown above.

Table A7 Bases for fuel properties in this publication

Property	As-fired or wet	Dry*	Dry ash free
Moisture content	C_m		
Ash content	C_a	C_{ad}	
Volatile content		C_{vd}	
Fixed carbon		C_{fd}	
Carbon content			C_C
Hydrogen content			C_H
Oxygen content			C_O
Gross calorific value			GCV

Note: * Basis used in Appendix for comparison of proximate analysis data for different biomass materials.

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