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**Validated methods for flue gas flow rate
calculation with reference to EN 12952-15**

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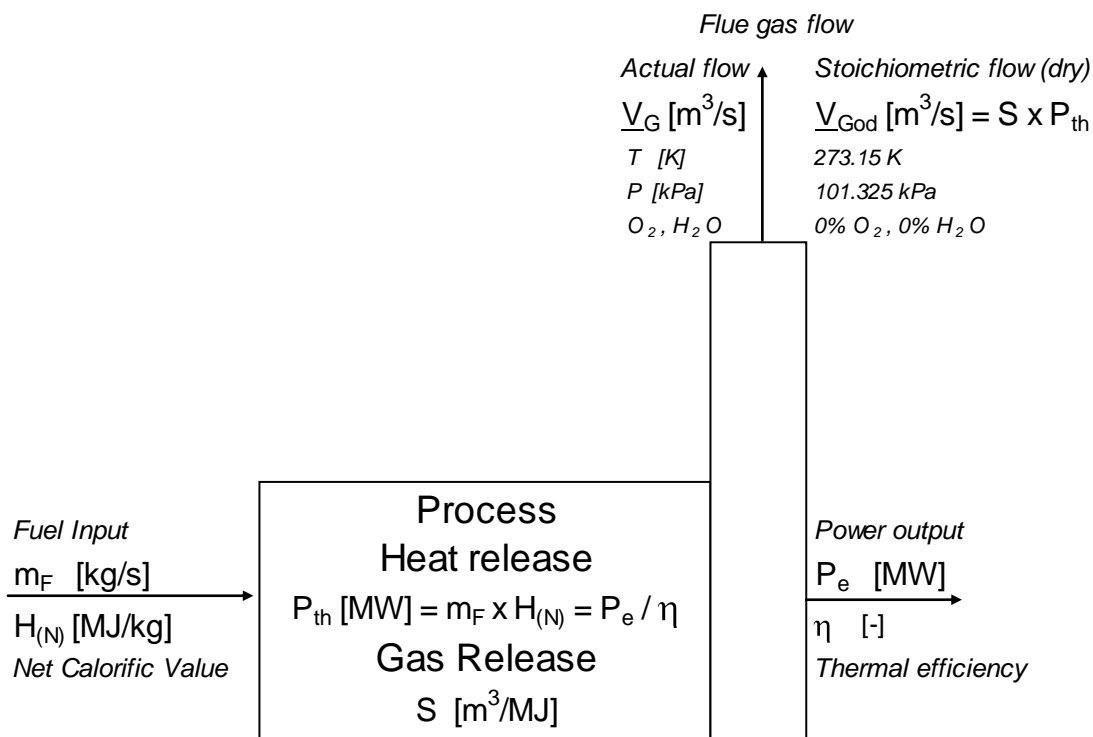
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EXECUTIVE SUMMARY

Operators of combustion plant need to know the flue gas flow rate to calculate the mass release of pollutant emissions. For many standard fuels, the calculation of flue gas flow rate gives reliable results, with a defined uncertainty, using relatively simple procedures. The calculated dry flue gas volume is combined with emission concentrations that are reported on a dry basis. When concentrations are also measured on a dry basis, as is often the case for large combustion plant, this avoids the measurement of water vapour and hence an additional uncertainty.



As shown in the schematic, the dry stoichiometric flue gas flow rate (m³/s) is obtained by multiplying the heat release (MW) by a fuel factor (m³/MJ). The heat release can be obtained directly, from the plant thermal input (fuel flow * net calorific value), or indirectly, from the power output divided by the thermal efficiency. On this basis, the fuel factor is very stable for a given type of fuel and it can be sufficient to use a fixed factor.

This encompasses the methods currently used within the European power industry, based on a brief industry survey. For solid fuel fired plant, hourly average flow rates are normally calculated from plant output and thermal efficiency but annual flue gas volumes are often calculated from annual fuel consumption and average fuel properties. When using a consistent set of input data, the results are comparable.

Fuel factor

Within this study it is shown that the European Standard EN 12952-15 is an important reference for flue gas calculation; the standard describes the basic principles and defines empirical formulas for flue gas calculation. This is not immediately apparent or obvious from the title: 'Water-tube boilers and auxiliary installations - Part 15: Acceptance tests'.

In this study, the important formulas from EN 12952-15 are presented and investigated. These yield the dry stoichiometric flue gas volume (0% O₂), at 273.15K and 101.325 kPa, per unit of fuel consumed. In principle, the stoichiometric calculation from the elemental composition of the fuel is the most accurate and reliable approach, based on representative fuel analyses:

$$V_{\text{God}} = 8.8930 \gamma_{\text{C}} + 20.9724 \gamma_{\text{H}} + 3.3190 \gamma_{\text{S}} - 2.6424 \gamma_{\text{O}} + 0.7997 \gamma_{\text{N}} \quad (\text{m}^3/\text{kg})$$

However, in many cases the elemental composition is not known or available for the fuel mix.

In this situation, the empirical formulas from EN 12952-15 for solid fuels, fuel oil and natural gas are a good alternative. These relate the flue gas volume to the net heating value of the fuel, $H_{(\text{N})}$ MJ/kg.

For solid fuels, such as coal and biomass, the ash and moisture mass fractions of the as received fuel must be taken into account:

$$V_{\text{God}} = -0.06018 (1 - \gamma_{\text{Ash}} - \gamma_{\text{H}_2\text{O}}) + 0.25437 (H_{(\text{N})} + 2.4425 \gamma_{\text{H}_2\text{O}}) \quad (\text{m}^3/\text{kg})$$

This type of calculation is based on the heating value of the fuel and is commonly used in the Netherlands. The equation is validated on three large datasets containing coal and biomass analyses. The calculated flue gas flow is compared with the reference flue gas flow calculated from the elemental composition. It is shown that, for a wide range of coal and biomass compositions, the above formula performs very well.

For light fuel oil the formula is: $V_{\text{God}} = 1.76435 + 0.20060 H_{(\text{N})}$ (m³/kg) and for natural gas: $V_{\text{God}} = 0.64972 + 0.22553 H_{(\text{N})}$ (m³/kg) or, using the volumetric net heating value at 0°C: $V_{\text{God}} = 0.199 + 0.234 H_{(\text{N})}$ (m³/m³).

For a range of natural gas compositions, encompassing the proposed European fuel supply standard, exact calculations of the stoichiometric flue gas volume are compared with the empirical EN 12952-15 calculations. The level of agreement is again very good. Validation on fuel oil has been limited to light fuel oils fired in gas turbines and boilers. For other liquid fuels, it is recommended that V_{God} is calculated from fuel composition.

However, it is noted that the flue gas volume per unit of supplied energy, S (m^3/MJ), is essentially invariant for a given fuel type and this is a better basis for calculation when compared with the flue gas volume per unit mass. The flue gas volume is derived from the combustible material in the fuel - and only the combustible material contributes to the calorific value. When the flue gas volume, per unit mass, is divided by the heating value, per unit mass, the influence of the inert fuel components is therefore largely accounted for. For a class of fuels with a given C:H ratio, the energy specific fuel factor is therefore very stable although the influence of fuel moisture in solid fuels needs to be accounted for; as the fuel moisture content increases, more fuel is required to provide the extra energy needed to evaporate the fuel moisture – resulting in a higher flue gas volume.

Since the fuel factor, on an energy basis, is very stable, it can be appropriate to use a fixed factor for each fuel type (limited to specific commercially traded fuels). The following table gives the fixed fuel factors and an associated uncertainty at 95% confidence. This approach is similar to that required by the US EPA which uses the gross (higher) heating value. Correcting for the different heating value definition, the fuel factors reported in this study and the US EPA fuel factors agree to within 0.8% for natural gas and 0.2% for light oil and hard coal.

Fuel Factor	Fuel type		
	Gas	Liquid	Solid
S <i>m^3/MJ at 0% O_2 dry 273.15K & 101.325kPa</i>	0.240	0.244	0.256
$U_{\text{R},95\%}$	$\pm 0.7\%$	$\pm 1.5\%$	$\pm 2.0\%$

For solid fuels, the fixed factor is acceptable for commercially traded hard coal and biomass with a moisture content below 25% by mass. At the reference oxygen concentration for solid fuels (6 vol%), this equates to a Fuel Factor of **0.359 m^3/MJ or 359 m^3/GJ** (c.f. 360 m^3/GJ recommended by the European Environment Agency). For liquid fuel, the tabulated fixed

factor is acceptable for light fuel oils and a factor of 0.248 m³/MJ is recommended here for Heavy Fuel Oil. For gaseous fuels, the fixed factor is acceptable for natural gas with a methane content higher than 80% by volume.

In all cases, the uncertainty can, of course, be reduced by relating the fuel factor to calorific value or fuel composition and this is necessary for some other fuels, e.g., natural gas with a low methane content, bio-oil or brown coal, although it may be sufficient to derive a different fixed factor that is specific to each defined fuel type.

Thermal input

The uncertainty of the flue gas volume also depends on the uncertainty of the thermal input. This is usually determined directly by fuel metering and CV determination - for gas and liquid fuels – with a combined uncertainty below $\pm 1.6\%$ (95% confidence) for large installations that comply with the requirements of the EU Emissions Trading Scheme.

Thermal input is often determined indirectly - from plant output and thermal efficiency - for solid fuels. In this case, the uncertainty needs to be determined on a case-by-case basis, at least for a given plant type and calculation approach. A case study for a coal fired power plant indicates that the worst case uncertainty in hourly thermal input is $\pm 4.8\%$ (95% confidence). This could be improved by correcting for ambient conditions and/or operational factors at the expense of robustness since only one input (plant load) is required in the simpler approach. The uncertainty for heating plant is lower, circa $\pm 2\%$, since the efficiency is higher and the thermal losses are lower.

Flue gas flow calculation

An appropriate performance requirement for the overall flue gas flow rate calculation, expressed as an achievable uncertainty at 95% confidence, is proposed below.

Fuel	Overall Uncertainty target
Gas	$\leq 2.0 \%$
Liquid	$\leq 3.0 \%$
Solid	$\leq 7.5 \%$

These uncertainties will, in practice, be lower if fuels of constant composition are used. It should be noted that these are the uncertainties for an hourly average flue gas flow rate but the calculation should be essentially bias free across a longer time period, e.g., for annual mass emission reporting. The residual uncertainty across an annual period should be similar to that achieved under the EU Emissions Trading Scheme with a materiality level of 2%.

Conclusions

Within this research project, it is demonstrated by validation that the flue gas flow calculation formulas from EN 12952-15 perform very well for a wide range of fuels. The EN 12952-15 standard is a suitable international reference for flue gas calculation. There are important requirements for reporting the mass emissions from combustion installations and it is important that calculation methods are underpinned by reference to international standards. The performance of the calculation methods is quantified and, in many cases, the calculation approach is superior to instrumental measurements. The authors therefore recommend the use of calculation methods as a cheap, accurate and relatively simple means of determining flue gas flow rate.

NOMENCLATURE

V_{God}	Flue gas volume (at 273.15K and 101.325 kPa) (per unit mass of fuel)	m^3/kg
G	Flue Gas (combustion gas)	
o	Stoichiometric	
d	Dry (basis)	
ar	as-received	
γ_{C}	Carbon content of fuel (by mass)	kg/kg
γ_{H}	Hydrogen content of fuel (by mass)	kg/kg
γ_{N}	Nitrogen content of fuel (by mass)	kg/kg
γ_{S}	Sulphur content of fuel (by mass)	kg/kg
γ_{O}	Oxygen content of fuel (by mass)	kg/kg
$\gamma_{\text{H}_2\text{O}}$	Water content of fuel (by mass)	kg/kg
γ_{Ash}	Ash content of fuel (by mass)	kg/kg
d	dry basis (fuel) as subscript	
ar	as received basis (fuel) as subscript	
$H_{(\text{N})\text{d}}$	Net Calorific Value (dry fuel)	$\text{MJ}/\text{kg}_{\text{d}}$
$H_{(\text{N})}$	Net Calorific Value (as-received fuel)	$\text{MJ}/\text{kg}_{\text{ar}}$
S	Fuel factor	m^3/MJ
K =	Energy specific fuel factor	m^3/MWh
η	Thermal efficiency (fractional)	-
P_{e}	Electrical output	MW
P_{h}	Heat output (excluding flue gas condenser)	MW
P_{prod}	Total energy output ($P_{\text{e}} + P_{\text{h}}$) (excluding energy produced by flue gas condenser units)	MW
P_{th}	Input fuel energy	MW
P_{hc}	Heat credits	MW
P_{losses}	Heat losses	MW
m	Fuel consumption	kg/s
$\underline{V}_{\text{God}}$	Flue gas flow rate (stoichiometric, dry)	m^3/s
\underline{V}_{G}	Flue gas flow rate (actual)	m^3/s

1 INTRODUCTION

Under the European Pollutant Transfer Register (E-PRTR) Regulation, those facility operators, to whom the Regulation applies, have to report the mass releases of pollutants to air to the competent authority in their Member State. Inventory reporting is also required by the Industrial Emissions Directive (IED). The release of pollutants has to be reported in kg or tonnes per year. This mass release calculation requires both flow and concentration data. It is important that the Power sector has a consistent, practical and cost effective means of reporting mass emissions.

For reporting concentrations, numerous analytical methods or predictive methods exist. Recently, the VGB European Working Group "European Pollutant Release and Transfer Register " compiled recommendations for calculating and reporting mass emissions (VGB / EURELECTRIC, 2008). For flue gas flow only three basic formulas are given, which are based on historic International Energy Agency (IEA) data. A quick comparison in the VGB Environmental Working Group "Emissions Monitoring" showed that calculation formulas for flue gas flow differ somewhat between companies and/or countries although the results are generally comparable. In the Netherlands, for example, official published calculation formulas exist, which are derived from DIN1942 (DIN, 1979).

For E-PRTR purposes, the reported release data can be based on calculation. For this, emission factors may be used, which are representative of certain pollutants and industrial sectors. However, the quality of the reported data should also be assured as stated in article 9 of the E-PRTR:

Article 9 Quality Assurance and Assessment

- 1 *The operator of each facility subject to the reporting requirements set out in Article 5 shall assure the quality of the information that they report. The competent authorities shall assess the quality of the data provided by the operators of the facilities referred to in paragraph 1, in particular as to their completeness, consistency and credibility.*

The new Industrial Emissions Directive (EU, 2010) explicitly requires the reporting of the annual mass emissions of SO₂, NO_x and dust for large combustion plant:

Article 72,3

For all combustion plants covered by Chapter III of this Directive, Member States shall, from 1 January 2016, establish an annual inventory of the sulphur dioxide, nitrogen oxides and dust emissions and energy input.

1.1 Rationale for the project

The primary aim of this project is to establish and document the calculation of flue gas volumetric flow rate based on the European standard EN 12952-15. The validation of the calculation approach is performed using compilations of measured fuel characteristics. The quality and robustness of the calculation methods is assessed by means of uncertainty calculations. Industry will be better able to decide on the best way of determining flue gas flow rate for different fuels and plant types. When calculating flue gas flow rate, consistent and validated methods are provided.

As noted above, it is of great importance to have accepted calculation methods available, with quantified uncertainties, in order to generate reliable emission mass release data. However, emission data can also be obtained by means of continuous measurement systems. Currently, stack flow calculation is mostly used by operators firing well characterised fuels and measurement is usually specified for waste incineration plant firing less well characterised fuels. For example, in Sweden about 200 bio-fuel fired plant use the calculation method, and are included in the Swedish NO_x-fee system, and fossil fired power plant calculate flue gas flow throughout Europe.

A measurement based standard for determining flue gas flow is being prepared by CEN TC 264 WG 23. However, it is recognised in this, and other, draft CEN standards that stack flow calculation can be an important alternative approach. It is important that accurate calculation methods are available and can be universally applied.

Measurement of the stack flow has a number of drawbacks when compared to calculation. In some plant, the flue gas flow velocity profile can be very asymmetric and variable and there is, of course, an uncertainty related to both the continuous monitor and the manual methods used for calibration of the monitor. The costs of ownership relating to maintenance, quality assurance and calibration of a continuous monitor are also high. Since all plants report concentration on a dry basis, and many actually measure on a dry basis, it is therefore simpler to calculate an annual mass emission if the flue gas flow is also available on a dry basis. Otherwise, the moisture content in the flue gas must also be measured continuously and this can lead to higher uncertainties and the addition of a relatively expensive instrument that is difficult to calibrate.

1.2 Benefits

When companies make use of a quality assurance system such as ISO 9001, or an environmental management system such as EMAS or ISO 14001, the reporting of the E-PRTR data can be included within that system to help to ensure the highest possible data quality. In some cases, reporting of mass emissions is also required for compliance purposes as specified in the site permit.

The results of this Research Project will benefit industry, external parties who deliver services or software to industry, and competent authorities in the following areas:

- Choice of the methods to be used for flue gas flow determination, including their applicability and accuracy
- An independent reference for the external verification of environmental compliance or trading reports
- Competent authorities can check the calculation of annual mass emission against standard methods and formulas
- Coal fired power plants, starting or increasing the co-firing of biomass or refuse derived fuel, can make reference to the applicability of the combined formulas and methods for calculation of flue gas flow
- software developers can use European wide accepted calculation methodologies for the power generation sector
- Contribution to the development of standards.

2 THE BASIC PRINCIPLES AND FORMULAS FROM EN 12952-15

Within this study it is recognised that the European Standard EN 12952-15:2003 is an important reference for flue gas calculation. This is not apparent from the title of the standard: 'Water-tube boilers and auxiliary installations - Part 15: Acceptance tests'. However, this standard is the European implementation of DIN 1942:1994 which first contained a number of empirical formulas for flue gas calculation. This report will therefore lead to a better understanding of EN 12952-15 and its use for flue gas flow calculation.

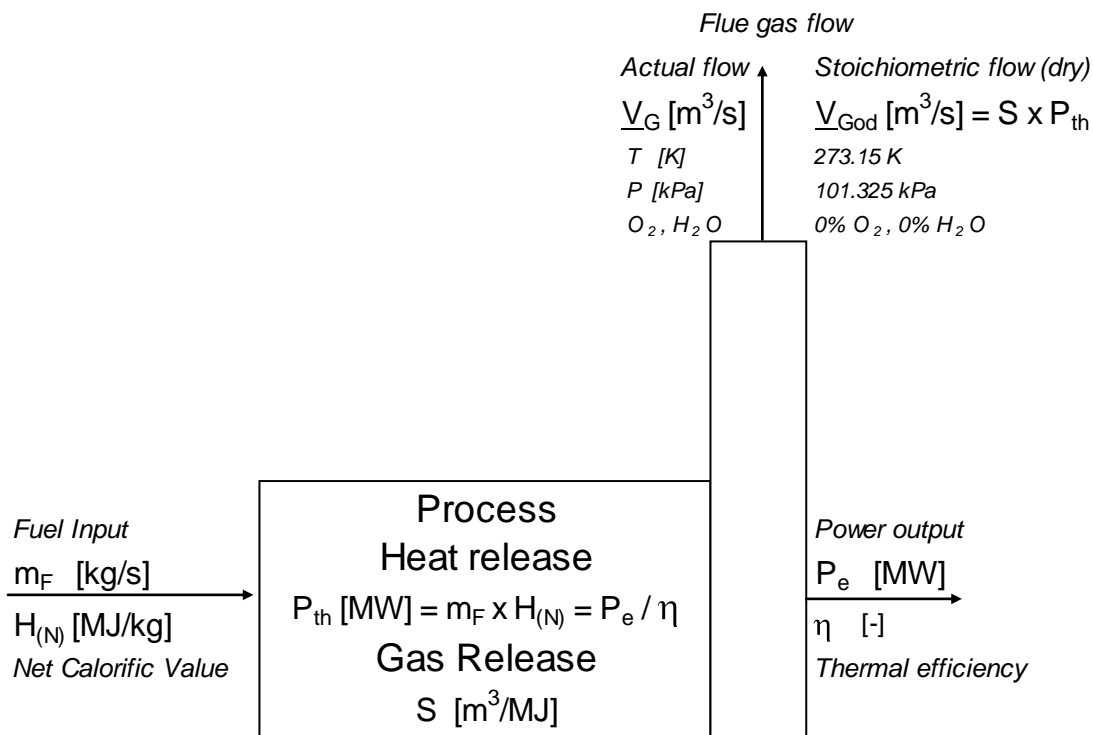


Figure 1.1 Over-view of stack gas flow calculation method

As shown in Figure 1.1, the dry stoichiometric flue gas flow rate ($\text{m}^3\text{/s}$) is obtained by multiplying the heat release (MW) by a fuel factor ($\text{m}^3\text{/MJ}$). The heat release can be obtained directly, from the plant thermal input (fuel flow * net calorific value), or indirectly, from the power output divided by the thermal efficiency. The fuel factor is very stable for a given type of fuel and it can be sufficient to use a fixed factor.

EN 12952-15 includes both empirical and fundamental formulas to calculate the flue gas volume per unit of fuel mass or heating value. Fuel consumption and heating value may be measured directly or determined indirectly from a heat and mass balance as also described in the standard.

Gas and liquid fuel flows are directly metered relatively easily and a low metering uncertainty can be achieved. This measured fuel/energy consumption can therefore be combined with a specific fuel factor that represents the flue gas volume release per unit mass or energy content of the fuel. This direct method is considered further in Section 5 alongside the validation of fuel factors for gas and liquid fuels.

Solid fuel consumption and heating value are harder to determine instantaneously and fuel/energy consumption is often calculated indirectly from the plant output (thermal and/or electrical) combined with the plant efficiency.

There are exceptions to the above general statements, e.g., solid fuel may be measured using gravimetric feeders or gas/oil fired systems may use plant efficiency as the basis of the flue gas calculation.

Section 2.1 now describes the calculation of the mass or energy specific fuel factor from either the fuel composition or the heating value of the fuel based on EN 12952-15. Section 2.2 illustrates the inter-relationships between the fuel factor formulas and gives example calculations.

2.1 Overview of EN 12952-15 formulas for specific flue gas volume

The primary reference for this investigation is EN 12952-15 and the embodied principles and calculation methods, referenced throughout this report, are explained in this section. For clarity and consistency, the abbreviations and terminology defined in EN 12952-15 are used throughout this report, wherever possible. A nomenclature is provided at the beginning of the report.

For solid fuels, the principle of flue gas flow calculation is to calculate the stoichiometric flue gas volume, V_{God} (m^3/kg fuel), from the 'as received' fuel analysis. The as received fuel contains both water and ash.

$$1 \quad V_{\text{God}} = 8.8930 \gamma_{\text{C}} + 20.9724 \gamma_{\text{H}} + 3.3190 \gamma_{\text{S}} - 2.6424 \gamma_{\text{O}} + 0.7997 \gamma_{\text{N}} \quad (\text{m}^3/\text{kg})$$

(Formula Nr. 8.3-60 on page 42 of EN 12952-15)

For solid fuels the empirical relation provided in EN 12952-15 is a good approximation for a wide range of solid fuels. This is also validated through the data sets in this report.

$$2a \quad V_{\text{God}} = -0.06018 (1 - \gamma_{\text{Ash}} - \gamma_{\text{H}_2\text{O}}) + 0.25437 (H_{(\text{N})} + 2.4425 \gamma_{\text{H}_2\text{O}}) \quad (\text{m}^3/\text{kg})$$

(Formula Nr. A.5N on page 85 of EN 12952-15)

The ash fraction has a minor influence only on V_{God} and can therefore be neglected in many cases. If the flue gas calculation is based on dry fuel, the water fraction is zero. Equation 2a can then be simplified to:

$$2b \quad V_{\text{God}} = -0.06018 + 0.25437 H_{(\text{N})\text{d}} \quad (\text{m}^3/\text{kg})$$

Where the heating value of the dry matter is: $H_{(\text{N})\text{d}} = (H_{(\text{N})} + 2.4425 \gamma_{\text{H}_2\text{O}}) / (1 - \gamma_{\text{H}_2\text{O}})$

For liquid fuels, the empirical calculation of the flue gas volume is given as:

$$3 \quad V_{\text{God}} = 1.76435 + 0.20060 H_{(\text{N})} \quad (\text{m}^3/\text{kg})$$

(Formula Nr. A.10N on page 86 of EN 12952-15)

For gaseous fuels, the empirical relation provided in EN 12952-15 is a good approximation for a wide range of fuel gases:

$$4a \quad V_{\text{God}} = 0.64972 + 0.22553 H_{(\text{N})} \quad (\text{m}^3/\text{kg})$$

(Formula A.15N on page 86 of EN 12952-15)

Since natural gas is often metered volumetrically, it can be more convenient to use a volume based formula:

$$4b \quad V_{\text{God}} = 0.199 + 0.234 H_{(\text{N})} \quad (\text{m}^3/\text{m}^3)$$

The derivation of the above formula is discussed in chapter 5.1.

If the stoichiometric flue gas volume is divided by $H_{(\text{N})}$ (net calorific value or lower heating value) then the flue gas volume is related to the MJ energy input (m^3/MJ fuel).

$$5 \quad S = V_{\text{God}} / H_{(\text{N})} \quad (\text{m}^3/\text{MJ})$$

This fuel factor, S , is essentially invariant for a given fuel type. In broad terms, this can be explained as follows. The flue gas volume is derived from the combustible material in the fuel; carbon oxidises to CO_2 , hydrogen oxidises to H_2O and so on for the minor constituents. The stoichiometric combustion of each fuel component requires a specified volume of air from which the oxygen is consumed and the remaining inert gas (principally nitrogen) contributes to the flue gas volume. Similarly, only the combustible material contributes to the calorific value of the fuel, representing the sum of the heat releases from the oxidation of the individual components. When the flue gas volume, per unit mass, is divided by the heating value, per unit mass, the influence of the inert fuel components is nullified. For a class of fuels with a given C:H ratio, the fuel factor is therefore essentially invariant.

It is therefore more meaningful to calculate the flue gas volume from the process thermal input and this also conveniently allows for the situation in which the thermal input is calculated using an indirect heat balance approach rather than being directly determined from the fuel consumption. Employing an energy specific fuel factor, \mathbf{S} , therefore provides a universal method for flue gas flow determination that is relatively insensitive to fuel variability.

For solid fuels, \mathbf{V}_{Gdd} can be calculated according to equation 1 or equation 2 for the average calorific value, water content and ash content of the fired fuels. This mass specific fuel factor increases with the water content of the fuel. That is, more wet fuel must be consumed, when compared with dry fuel, in order to release the additional energy required to evaporate the water that is present in the fuel.

Using the indirect methods described in EN 12952-15, the fuel energy input can be calculated from the thermal efficiency (η) and the hourly average output load (\mathbf{P}_{prod}). The system limit concerning the indirect method to calculate the plant efficiency and the flue gas flow must be defined to exclude flue gas condensers. The principle of a condenser is that the plant produces extra energy from the condensation of the water, which is not accounted for in the lower heating value $H_{(\text{N})}$.

Since the water content of a fuel has a negative contribution to the net calorific value its influence on the heating value must be properly accounted for. This will be illustrated in more detail in the following chapters. It should be noted that calculations of flue gas flow rate and energy consumption must be self consistent.

2.2 Example of the use and interdependence of the EN 12952-15 formulas

The interdependence of the equations given in section 2.1 is best illustrated by an example calculation. An average coal composition is used for these purposes:

Parameter	Notation	Value	Unit
Carbon	γ_C	0.718	kg/kg _d
Hydrogen	γ_H	0.045	kg/kg _d
Nitrogen	γ_N	0.015	kg/kg _d
Sulphur	γ_S	0.010	kg/kg _d
Oxygen	γ_O	0.082	kg/kg _d
Ash	γ_{Ashd}	0.130	kg/kg _d
Water	γ_{H_2O}	0.130	kg/kg _{ar}
Ash	γ_{Ash}	0.113	kg/kg _{ar}
Net Calorific Value (dry fuel)	$H_{(N)d}$	28.33	MJ/kg _d
Net Calorific Value (wet fuel)	$H_{(N)}$	24.33	MJ/kg _{ar}
Thermal Efficiency (fractional)	η	0.400	- (fractional)
Electrical output	P	1	MW _e

Stoichiometric flue gas flow based on the dry fuel mass fractions:

$$V_{God} = 8.8930 \gamma_C + 20.9724 \gamma_H + 3.3190 \gamma_S - 2.6424 \gamma_O + 0.7997 \gamma_N$$

$$= 7.16 \text{ m}^3/\text{kg}_d$$

Dividing by the heating value (dry) gives the fuel factor:

$$S = V_{God} / H_{(N)d} = 7.16 / 28.33$$

$$= \mathbf{0.2526 \text{ m}^3/\text{MJ}}$$

This factor can be calculated for the as received basis either by using the as received fuel composition directly in the above formula or by recalculating from the dry result as follows:

$$V_{God} = 7.16 * (1 - \gamma_{H_2O})$$

$$= 6.23 \text{ m}^3/\text{kg}_{ar}$$

Dividing by the heating value (ar) gives the fuel factor for the as received fuel:

$$S = V_{God} / H_{(N)} = 6.23 / 24.33$$

$$= \mathbf{0.2559 \text{ m}^3/\text{MJ}}$$

At the reference oxygen concentration of 6 vol% this gives:

$$S = (20.94)/(20.94-6) * 0.2559 = 1.4016 * 0.2559 \\ = \mathbf{0.3587 \text{ m}^3/\text{MJ}} \text{ or } 358.7 \text{ m}^3/\text{MJ}$$

Using the empirical formulas of EN 12952-15 based on net calorific value

$$V_{\text{God}} = -0.06018 + 0.25437 H_{(\text{N})\text{d}} \\ = 7.15 \text{ m}^3/\text{kg}$$

Dividing by the heating value gives the fuel factor:

$$S = V_{\text{God}} / H_{(\text{N})\text{d}} = 7.15 / 28.33 \\ = \mathbf{0.2522 \text{ m}^3/\text{MJ}}$$

And the calculation on the as-received basis:

$$V_{\text{God}} = -0.06018 (1 - \gamma_{\text{Ash}} - \gamma_{\text{H}_2\text{O}}) + 0.25437 (H_{(\text{N})} + 2.4425 \gamma_{\text{H}_2\text{O}}) \\ = 6.22 \text{ m}^3/\text{kg}_{\text{ar}}$$

Dividing by the heating value gives the fuel factor for the as received fuel:

$$S = V_{\text{God}} / H_{(\text{N})} = 6.22 / 24.33 \\ = \mathbf{0.2558 \text{ m}^3/\text{MJ}}$$

It can be seen that the empirical correlation delivers a result that is very close to the exact determination from fuel composition.

Using the indirect approach; thermal input from plant output and efficiency

The energy specific fuel factor (m^3 flue gas per MJ) is relatively insensitive to fuel variations and can be multiplied by the plant thermal input in order to calculate the flue gas flow rate. The plant thermal input can be determined directly from fuel metering or indirectly from plant output and efficiency as discussed later.

Using the above example, the calculation of the flue gas flow from an hourly average load, P_e , of 1 MWe generated at a thermal efficiency, η , of 40%:

$$\underline{V}_{\text{God}} = S \times P_e / \eta = 0.2558 \times 1 / 0.40 \\ = \mathbf{0.6395 \text{ m}^3/\text{s}}$$

3 CALCULATION METHODS FOR COAL AND ANALYSIS OF VARIATIONS

Most of the European power industry methods are based on fuel consumption combined with fuel composition and this approach is particularly suited to calculating the longer term total emitted stack volume. The general approach is to calculate the dry flue gas flow at normalised conditions (0% oxygen; 273.15 K; 101.325 kPa). The lower heating value is the general starting point for fuel flow calculations in Europe. For solid fuels like coal the average stoichiometric fuel factor is circa 0.25 m³/MJ.

3.1 Overview of flue gas flow calculation methods across Europe for coal firing

In the VGB Environmental Working Group “Emissions Monitoring” a brief survey has been made of the calculation formulas and methods employed in several European countries for coal firing as summarised in the table below - which also includes other approaches and fixed fuel factors defined by various bodies.

Country	Formula	Based on	Comment
France	$\underline{V}_{\text{God}} = P_e * K$	Electrical output	K is updated annually from total fuel consumption and total generation (not load dependent)
Italy	$\underline{V}_{\text{God}} = m * V_{\text{God}}$	Fuel input	Annual flue gas volume is calculated from total fuel consumption (V_{God} is fixed factor)
UK	$\underline{V}_{\text{God}} = P_e * S / \eta$	Electrical output	η is updated annually from total fuel consumption and total generation (load dependent)
Ireland	$\underline{V}_{\text{God}} = m * V_{\text{God}}$	Fuel input	V_{God} calculated from fuel composition
Sweden	$\underline{V}_{\text{God}} = m * V_{\text{God}}$	Fuel input	V_{God} calculated from fuel composition
Netherlands	$\underline{V}_{\text{God}} = m * V_{\text{God}}$	Fuel input	V_{God} calculated from Net CV
US EPA	$\underline{V}_{\text{God}} = m * \text{GCV} * S$	Fuel input	Based on Gross thermal input. Fixed value of S (for each fuel type) or calculated from fuel composition
E-PRTR			Fixed value of S (350 m ³ /GJ at 6% oxygen)

European Env. Agency			Fixed value of S (360 m ³ /GJ at 6% oxygen)
Int. Energy Agency	$\underline{V}_{\text{God}} = P_e * S / \eta$	Electrical output	Fixed value of S (364 m ³ /GJ at 6% oxygen)

P_e = Hourly average load (MWe)

K = Energy specific fuel factor (m³/MWh)

S = Energy specific fuel factor (m³/MJ)

η = Thermal efficiency (-)

GCV = Gross Calorific Value

There are differences in the averaging periods, the reference oxygen contents and the reference temperatures. The fuel input approach is usually based on total fuel consumption and total volume released in a specified reporting period. The equations used for calculating the fuel factor from fuel composition are very similar to Equation 1 (Section 2.1).

Various fixed values of stack flow factor are also defined as shown in the table. The E-PRTR value is 3% lower than that used by the European Environment Agency. The IEA value is 1% higher and is based on the factor currently used in the UK.

In summary:

- France and the UK consistently use electrical output to calculate thermal input
- Other EU countries use a fuel input approach with many minor variations
- The most common method internationally is based on heat input being multiplied by an appropriate fuel factor to give the flue gas flow volume
- The calculation method directly based on the heating value of the fuel is not commonly used (only Sweden and Netherlands)
- Stoichiometric calculations are commonly used for mass specific or energy specific fuel factors.

With a consistent set of input data the different power industry approaches all deliver an answer within one percent. However, differences can arise due to the incorrect treatment of water content as discussed later.

3.2 Comparison with US-EPA calculation methods

The US EPA methodology defines a range of stoichiometric stack gas flow factors. In situations when flue gas flow monitoring is not required, or the monitor is not available, the US EPA defines default factors for various fuels (40 CFR Part 75, Appendix F section 3.3 – Conversion Procedures) as shown in the Table below.

The fuel factors are given as dry standard cubic feet (dscf) per million Btu (mmBtu) where the volume is referenced to 20 °C (68 F) and 29.92 inches of mercury (101.325 kPa) and the heat is based on the gross (upper) calorific value.

The EPA factors are converted to $\text{m}^3/\text{MJ}_{\text{net}}$ in the Table below and are then compared with the fixed factors later proposed for commercially traded fossil fuels. The deviations are small (within $\pm 1\%$) and are discussed later.

Fuel	US EPA			US EPA EN12952-15		
type	dscf/mmBtu	m^3/MJ_g	$\frac{\text{MJ}_{\text{net}}}{\text{MJ}_{\text{gross}}}$	m^3/MJ_n	m^3/MJ_n	Δ (%)
Natural Gas	8710	0.218	0.900	0.242	0.240	0.8%
Oil	9190	0.230	0.941	0.244	0.244	0.1%
Coal bituminous	9780	0.245	0.958	0.255	0.256	-0.2%
sub-bituminous	9820	0.246	0.958	0.256	0.256	0.2%

The following examples show that the fixed factors are in accordance with EN12952-15 when calculated for some average fuels:

Gas with a heating value $H_{(N)}$ of 43.5 MJ/kg:

$$\begin{aligned}
 S &= V_{\text{God}} / H_{(N)} = (0.64972 + 0.22553 H_{(N)}) / H_{(N)} \\
 &= (0.64972 + 0.22553 * 43.5) / 43.5 \\
 &= \mathbf{0.240} \text{ m}^3/\text{MJ}
 \end{aligned}$$

Oil with a heating value $H_{(N)}$ of 41 MJ/kg:

$$\begin{aligned}
 S &= V_{\text{God}} / H_{(N)} = (1.76435 + 0.20060 H_{(N)}) / H_{(N)} \\
 &= (1.76435 + 0.20060 * 41) / 41 \\
 &= \mathbf{0.244} \text{ m}^3/\text{MJ}
 \end{aligned}$$

Coal with a $H_{(N)}$ of 24.33 MJ/kg_(ar), water fraction (γ_{H_2O}) of 0.13 kg/kg and ash fraction (γ_{Ash}) of 0.113 kg/kg_{ar}:

$$\begin{aligned} S &= V_{\text{God}} / H_{(N)} \\ &= (-0.06018 (1 - \gamma_{\text{Ash}} - \gamma_{H_2O}) + 0.25437 (H_{(N)} + 2.4425 \gamma_{H_2O})) / H_{(N)} \\ &= (-0.06018 (1 - 0.113 - 0.130) + 0.25437 (24.33 + 2.4425 \cdot 0.13)) / H_{(N)} \\ &= \mathbf{0.256 \text{ m}^3/\text{MJ}} \end{aligned}$$

4 THERMODYNAMIC CALCULATIONS; OUTPUT BASED APPROACH

4.1 Principles of the output based approach

This calculation method is based on the relation between net electrical output and flue gas flow for solid and liquid fuels. For coal fired power plants with co-combustion of secondary fuels (either solid or liquid) the methodology of the flue gas flow will be derived and evaluated.

For solid fuels with a directly measured fuel consumption rate using, for example, calibrated gravimetric feeders, and a stable fuel composition (calorific value), a low uncertainty is achievable. However, in many situations, the instantaneous fuel consumption and calorific value are not available and the energy consumption must be derived from the plant output, P_e (MW_e) and the fractional thermal efficiency, η (-):

$$P_{th} = P_e / \eta$$

The uncertainty of the thermal efficiency must be justified for compliance purposes. For example, a coal fired power plant, with an established heat accountancy and fuel management system, has an uncertainty of the instantaneous thermal efficiency of circa $\pm 5\%$ (Section 4.3). This can be reduced to circa $\pm 3\%$ with on-line correction of the efficiency calculation to account for changes in plant operation and ambient conditions.

4.2 Calculation of flue gas flow rate

The stoichiometric dry flue gas flow rate at 273.15 and 101.325 kPa, \underline{V}_{God} (m³/s) is calculated from the fuel factor, S , and the thermal input P_{th} :

$$\underline{V}_{God} = S P_{th}$$

For mass emission reporting, this volumetric flue gas flow rate is corrected to the required standard reference oxygen content:

$$\underline{V}_{Gd} = 0.2094 \underline{V}_{God} / (0.2094 - \gamma_{O2r})$$

where γ_{O_2r} is the dry oxygen reference condition for the plant as a dry volume fraction. For boilers, this is normally 0.03 for gas and liquid fuels and 0.06 for solid fuels and for gas turbines this is normally 0.15.

The uncertainty related to the oxygen concentration measurement is not included in the uncertainty budget for mass emission reporting. Indicative uncertainties for the flue gas flow rate at the required reference conditions are shown in Table 4.1, based on the uncertainties given in subsequent sections. Note that standard uncertainties are quoted for the fuel factor and thermal input and these are combined to give the expanded uncertainty, at 95% confidence, for each fuel type.

Table 4.1 Indicative uncertainty

Fuel	S m ³ /MJ u_R (%)	P_{th} MW u_R (%)	V_{God} m ³ /s u_R (%)
Natural Gas	0.4	0.8	1.8
Fuel oil	0.8	0.8	2.2
Hard coal	1.0	2.4	5.1

Additional corrections are required when calculating the flue gas flow rate at the free stream conditions in the flue gas:

$$\underline{V}_G = \frac{0.2094}{(0.2094 - \gamma_{O_2})} \frac{1}{(1 - \gamma_{H_2O})} \frac{T}{273.15} \frac{101.325}{p} \underline{V}_{God}$$

where

γ_{O_2} is the flue gas oxygen content, dry volume fraction

γ_{H_2O} is the flue gas water content, wet volume fraction

T is the flue gas temperature, K

p is the flue gas pressure, kPa

The uncertainties related to the flue gas oxygen, moisture, temperature and pressure must then be combined with the uncertainty of the reference flue gas flow rate.

4.3 Uncertainty of the flue gas volume using the output based approach

Since the thermal efficiency of the plant is a function of the load (electrical output), the uncertainty related to the efficiency determination also needs to be considered. This is, in turn, dependent upon the approach taken to the efficiency calculation, i.e., whether or not the method takes into account plant operational parameters which increases the accuracy of the approach at the expense of a greater number of input parameters and reduced robustness.

As explained above, the thermal input can be used to calculate the fuel consumption, knowing the heating value of the fuel, with the subsequent uncertainty determined from the thermodynamic approach described below. Alternatively, the flue gas volume per unit thermal input can be used. If a constant value of fuel factor is assumed, the related uncertainty must also be considered.

Case study: coal fired power plant

The Unit hourly flue gas flow rate is determined from the Unit electrical output and efficiency as follows:

$$\underline{V}_{\text{God}} = S \times P_e / \eta$$

Where

P_e is the unit load (MW_e), η = unit thermal efficiency (fractional) (-) and S is the fuel factor, (m^3/MJ).

Each component in the calculation is now considered in order to build up an overall uncertainty budget.

Unit load

In this example, the Unit load, P , is the generated output for the Unit (not the exported electricity). The generated output is less sensitive to differences in works power consumption. For example, a boiler fitted with Flue Gas Desulphurisation has a higher works power associated with the operation of the SO_2 removal process.

Unit load is a high quality, continuously available measurement that is used for fiscal accounting. The overall uncertainty associated with the meters of the type and size used in the power industry is better than $\pm 0.5\%$ at 95% confidence [UK Balancing and Settlement Code of Practice].

Fuel factor

The fuel factor for internationally traded hard coal is given as 0.256 m³/MJ at 0% O₂, dry. 273.15K, 101.325 kPa), as noted in Section 3.2. This is approximately equivalent to 0.360 m³/MJ at the reference oxygen concentration normally used for coal firing (6% O₂ dry), corresponding to the value used by the European Environment Agency. Although, this factor can be determined for individual coal samples (from composition and net CV), the uncertainty associated with a fixed factor, based on the analysis of a number of fuel databases, is $\pm 2.0\%$ at 95% confidence (Chapter 6.2.4).

Unit efficiency

The Unit efficiency definition is consistent with the Unit load definition above, i.e., this is a MW generated NCV basis. The generated efficiency varies slightly between Minimum Stable Generation (MSG) and Maximum Continuous Rating (MCR) for a coal fired Station. Efficiency data for three Stations are plotted in Figure 4.1 below in which the fractional efficiency is plotted against fractional unit load (the load divided by MCR). The efficiency drop between MCR and MSG is typically about 2.5 percentage points. The efficiencies given in Figure 4.1 are calculated using a plant performance modelling tool.

Since it is difficult to produce efficiency curves for all Units, and for simplicity, it is appropriate to use a fixed gradient straight line across the load range of interest, as shown in Figure 4.1. It can be seen that the errors between the calculated efficiency points and the straight lines are small.

The uncertainty in the efficiency-load relationship can be evaluated, using performance modelling software, by imposing a maximum variation in each of the parameters that influences the efficiency. This is illustrated in Table 4.2 which shows the impact of each operational component on the Unit efficiency at four load points. The resultant uncertainty band is plotted in Figure 4.2 and these uncertainties are ranked in Figure 4.3. It can be seen that the total uncertainty in the efficiency is of the order of 1.4 percentage points. If the most important influencing factors are corrected by on-line compensation, this uncertainty would reduce to about 0.75 percentage points.

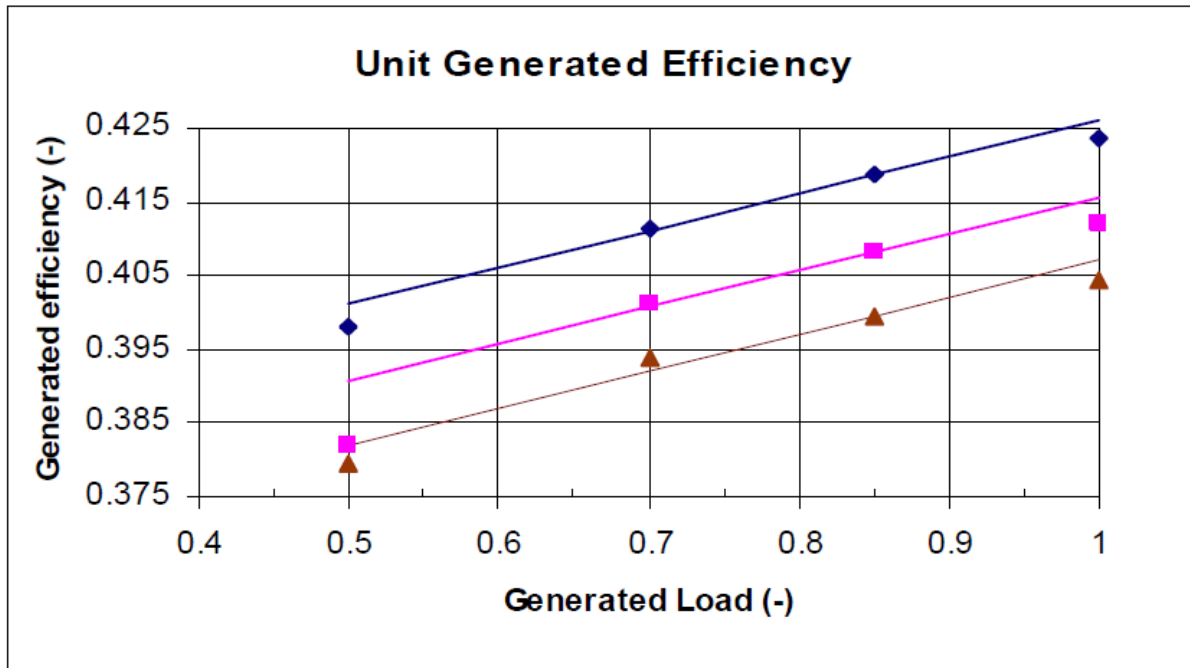


Figure 4.1 Efficiency – load curves for three different coal fired power plant

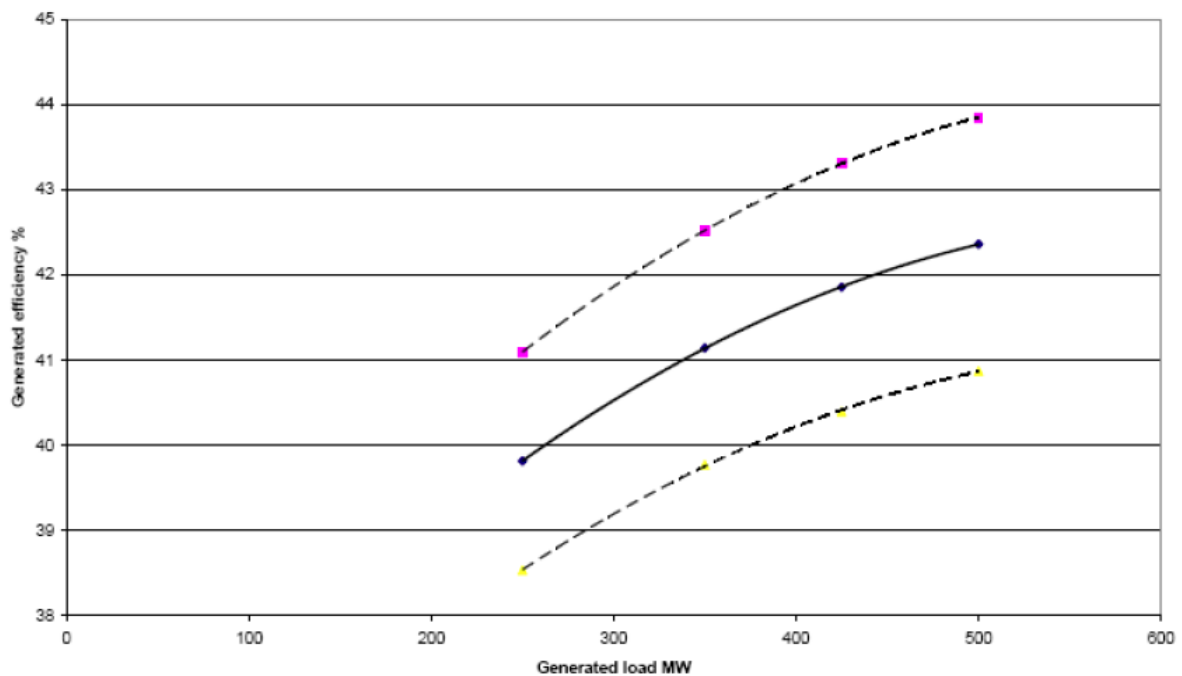


Figure 4.2 Uncertainty band for a given coal fired power plant

Table 4.2 Effects of Operational Variations on Generated Efficiency

					Generated load MW				
					500	425	350	250	
					Generated efficiency %	42.36	41.86	41.14	39.81
Group	Description	Datum Plant Values	Variation	Units	Generated efficiency change % points				
boiler air temp	Boiler air temperature	30	10	°C	0.087	0.092	0.093	0.099	
ambient air humidity	ambient air humidity	60	30	%	-0.008	-0.009	0.002	0.001	
Final S/H temperature	Final S/H temperature	568	10	°C	0.007	0.005	0.113	0.139	
Final R/H temperature	Final R/H temperature	565	10	°C	0.000	0.000	0.000	0.000	
Final boiler pressure	Final boiler pressure	156	10	bar a	-0.016	-0.018	-0.042	-0.038	
CW inlet temperature	CW inlet temperature	18	7	°C	-0.856	-0.867	-0.827	-0.851	
Fouling	Furnace Wall Fouling Resistance	5	1	m² K/kW					
Fouling	pri platen S/H Bank Fouling Res	15	5	m² K/kW					
Fouling	sec platen S/H Bank Fouling Res	10	5	m² K/kW					
Fouling	2nd s/s/h Bank Fouling Res	8	7	m² K/kW					
Fouling	prim s/h Bank Fouling Res	6	4	m² K/kW					
Fouling	sec r/h Bank Fouling Res	10	10	m² K/kW					
Fouling	prim r/h Bank Fouling Res	15	10	m² K/kW					
Fouling	economiser below prim s/h Bank Fouling Res	4	6	m² K/kW					
Fouling	economiser below prim r/h Bank Fouling Res	4	6	m² K/kW	-0.410	-0.388	-0.260	-0.107	
Fraction gas flow to p/s/h	Fraction gas flow to p/s/h	0.35	0.10		0.026	-0.079	-0.107	-0.105	
Tramp air inleakage	Tramp air inleakage	0.07	0.07	-	0.096	-0.010	-0.040	-0.044	

Boiler exit O2	Boiler exit O2	Fitted to O2 Vs load curve	2	% dry by vol	-0.617	-0.714	-0.724	-0.623
FUEL TEMP	FUEL TEMP	25.00	-5	°C	-0.010	-0.010	-0.009	-0.009
ASH FRACTION	ASH FRACTION	0.087	0.033	-	-0.120	-0.118	-0.095	-0.092
MOISTURE FRACTION	MOISTURE FRACTION	0.097	0.053	-	-0.186	-0.186	-0.078	-0.075
DAF fuel composition	HYDROGEN DAF FRACTION	0.0493	0.00493	-	-0.050	-0.048	-0.020	-0.018
DAF fuel composition	OXYGEN DAF FRACTION	0.1115	0.01115	-				
DAF fuel composition	NITROGEN DAF FRACTION	0.0176	0.00176	-				
DAF fuel composition	SULPHUR DAF FRACTION	0.0085	0.00085	-				
CARBON IN ASH	CARBON IN ASH	0.039	0.031	-	-0.191	-0.189	-0.169	-0.164
unaccounted losses	unaccounted losses	0.5	0.5	-	-0.216	-0.212	-0.228	-0.222
HP heater out of service	HP heat out of service	in	out	-	-0.644	-0.562	-0.485	-0.386
BFPT out of service	BFPT out of service	in	out	-	0.606	0.513	0.489	0.487

The cumulative ranked uncertainties shown in Figure 4.3 are common to most coal fired units across Europe although some contributions are design specific. For example, the boiler feed water pump can be driven by electricity or steam at this plant and the choice of motive power gives rise to the fourth largest uncertainty. Figure 4.3 shows how the uncertainties could be reduced by accounting for the variability of the operating conditions that affect efficiencies from the most significant effect down to the least significant effect.

For example, the effect of condenser cooling water temperature (and hence condenser pressure), and the flue gas oxygen content, can be compensated for. However, the most

robust approach is to use only one measured plant signal – the generated load – and accept a somewhat higher random uncertainty that is not so important across the longer term.

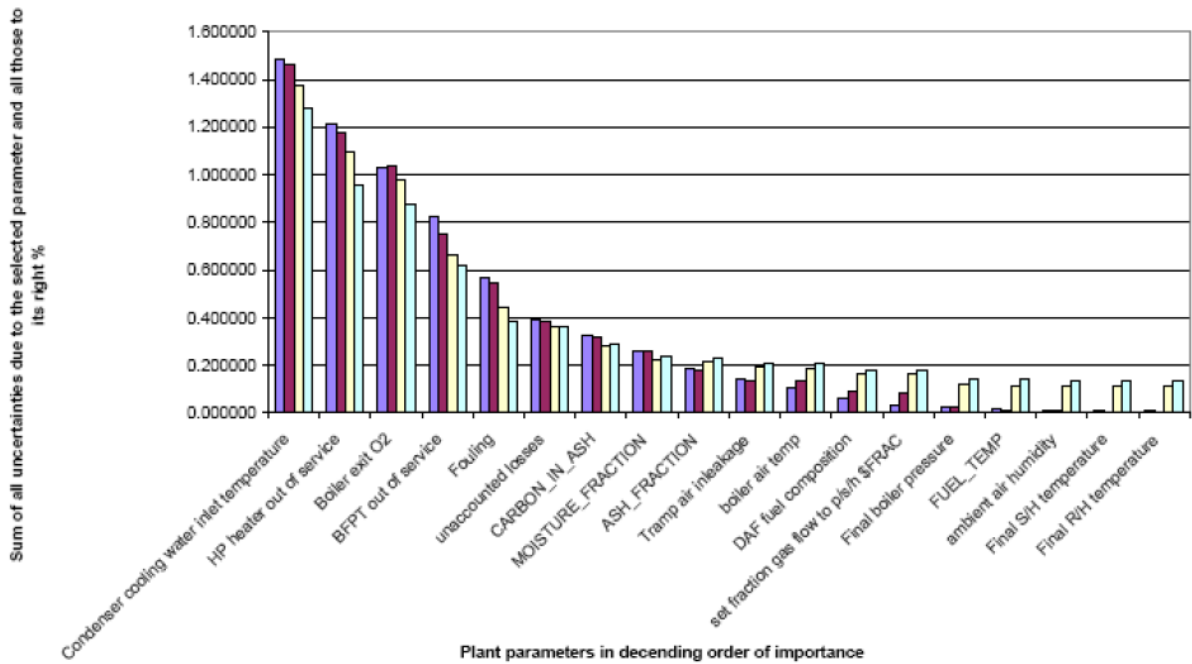


Figure 4.3 Ranked uncertainty contributions from operational parameters

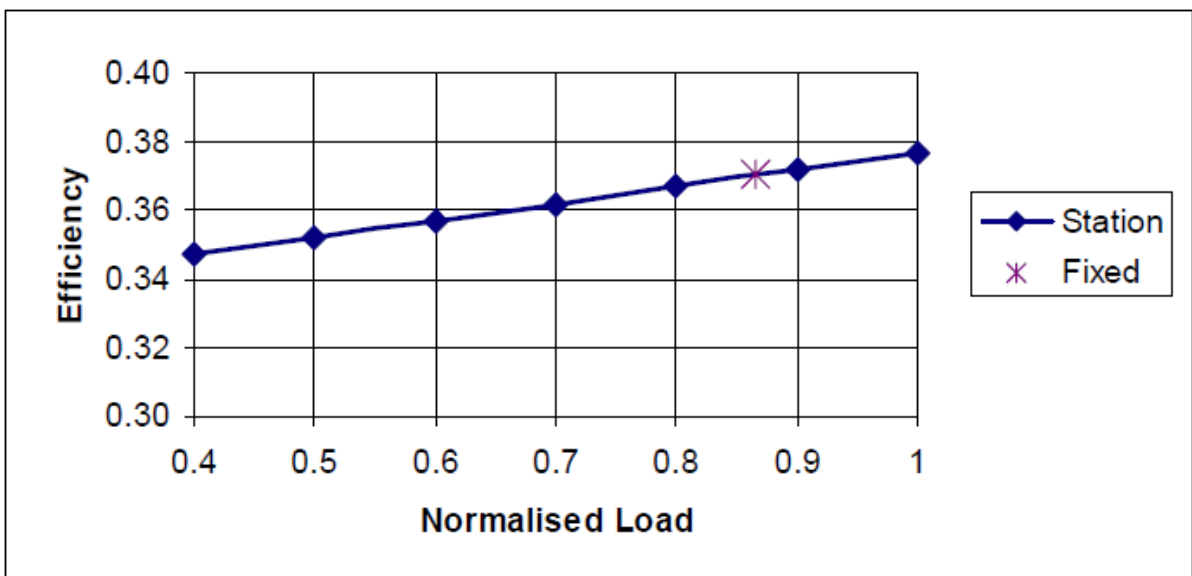


Figure 4.4 Efficiency – load relationship constructed from the fixed average load point

In this case study, the small variation of thermal efficiency with load is represented a linear fit as shown in Figure 4.4. This shows a fixed operation point, from which the efficiency is scaled, that can be related to an EU ETS report as follows:

- Convert the reported fuel burn to energy input using the reported NCVs
- Determine the annual generated electrical output
- Calculate the average efficiency from the output and input energy values
- Calculate the average annual generated load from the generated output and the operating hours.

This analysis can be further refined by considering the proportion of the fuel energy that is used in start-up and shut-downs.

Overall uncertainty

The uncertainty of the individual components that are used in the stack flow calculation has been discussed above, noting that these are expressed at the 95% confidence level. The power measurement is the most certain component ($\pm 0.5\%$). The uncertainty in the fuel factor is of the order of $\pm 2.0\%$.

The relative uncertainty of the generated plant efficiency (instantaneous) is $\pm 3.8\%$. Some allowance should also be made for the uncertainty in the input heat data used for calculating this efficiency point. The uncertainty of fuel and energy use reported under the EU ETS Monitoring and Reporting Guidelines is of the order of $\pm 1\%$. The Station efficiency uncertainty estimate of $\pm 3.8\%$ has therefore been increased, arbitrarily, to $\pm 4.8\%$ to account for this and also third order influences.

The overall uncertainty is then calculated using a standard root mean square approach using standard uncertainties:

$$u_{\text{TOTAL}} = (u_{\text{LOAD}}^2 + u_{\text{FUEL}}^2 + u_{\text{EFFICIENCY}}^2)^{0.5}$$

Table 4.3 Combined uncertainties for a typical coal fired power station

Component	Units	Standard Uncertainty %
Power	MWe	0.25
Fuel factor	m ³ /MJ	1.0
Efficiency	-	2.4
Overall uncertainty	%	2.6
Expanded Uncertainty	%	5.1

Table 4.3 gives an estimate of the overall uncertainty of the Station hourly average stack flow calculation of $\pm 5.1\%$ at 95% confidence. The introduction of a three-term on-line efficiency correction could reduce the overall uncertainty to circa $\pm 3.6\%$. In any event, the uncertainty in the long term average stack flow should be better than circa $\pm 2\%$.

Case study: Biomass fired steam raising plant

EN 12952-15 chapter 8.4.2 defines an indirect method for the calculation of thermal efficiency and energy input.

In this method the produced energy and the energy losses are measured.

The thermal efficiency $\eta = P_{\text{prod}}/P_{\text{input}}$

$$P_{\text{input}} = P_{\text{th}} + P_{\text{hc}}$$

$$P_{\text{th}} = \text{input fuel energy}$$

$$P_{\text{hc}} = \text{heat credits (added electrical energy, for example, a flue gas fan can raise the flue gas temperature by 2-3 }^{\circ}\text{C)}$$

and

$$P_{\text{input}} = P_{\text{prod}} + P_{\text{losses}}$$

$$P_{\text{losses}} = P_{\text{rad}} + P_{\text{ash}} + P_{\text{unb}} + P_{\text{GF}}$$

$$P_{\text{rad}} = \text{radiation losses}$$

$$P_{\text{ash}} = \text{ash losses (sensible enthalpy losses and unburned material)}$$

$$P_{\text{unb}} = \text{losses in unburned CO and TOC in the flue gas}$$

$$P_{\text{GF}} = \text{sensible enthalpy losses in the flue gas}$$

This leads to:

$$P_{\text{th}} = P_{\text{prod}} + P_{\text{rad}} + P_{\text{ash}} + P_{\text{unb}} + P_{\text{GF}} - P_{\text{hc}}$$

Most of the losses are calculated by stoichiometric formulas similar to those described in chapter 2.2, but others, for example the radiation losses from the boiler, are read from diagrams in EN 12952-15.

To calculate the hourly dry flue gas flow at the flue gas oxygen content (273.15K, 101.325 kPa):

$$\underline{V}_G = P_{\text{th}} * S * 20.94 / (20.94 - O_2) * 3600 \quad \text{m}^3/\text{h}$$

An uncertainty budget performed in accordance with the GUM, for a biomass with 40% moisture content, gives an uncertainty of about $\pm 7\%$. The components with the highest uncertainties are γ_C , γ_H , $H_{(N)}$ and the oxygen content in the flue gas which can, in many cases, be neglected.

The above approach describes the calculation of thermal input from the measured produced energy and the thermal losses or gains, some of which are difficult to measure instantaneously. It is also possible to calculate a value of the plant performance (η) based on EN 12952-15. In the Table below the plant performance has been calculated in accordance with EN 12952-15 by varying the main input parameters for the same biomass case with 40 % moisture content. This example is from a heat producing plant.

Table 4.4 Plant performance calculation in accordance with EN 12952-15

Fuel	P_{prod}	O_2	t_G	CO	P_{ash}	P_{rad}	η	V_{God}
	MW		Temp, flue	CO flue gas				
	prod	vol % dg	gasgr C	mg/m ³ n	MW	MW		
Bio fuel, 60 % TS	100	6	130	100	0.3	0.8	92.4	147400
Bio fuel, 60 % TS	100	4	130	100	0.3	0.8	93.0	129100
Bio fuel, 60 % TS	100	8	130	100	0.3	0.8	91.5	171800
Bio fuel, 60 % TS	100	6	150	100	0.3	0.8	91.1	149400
Bio fuel, 60 % TS	100	6	110	100	0.3	0.8	93.6	145400
Bio fuel, 60 % TS	100	6	130	2000	0.3	0.8	91.6	148600
Bio fuel, 60 % TS	100	6	130	0	0.3	0.8	92.4	147400
Bio fuel, 60 % TS	100	6	130	100	0.6	0.8	92.1	147900
Bio fuel, 60 % TS	100	6	130	100	0	0.8	92.6	147000
Bio fuel, 60 % TS	100	6	130	100	0.3	1.6	91.6	148600
Bio fuel, 60 % TS	100	6	130	100	0.3	0	93.1	146200
Bio fuel, 60 % TS	200	6	130	100	0.3	0.8	92.8	294400
Bio fuel, 60 % TS	50	6	130	100	0.3	0.8	91.4	73900
Bio fuel, 40 % TS	100	6	130	100	0.3	0.8	90,9	170100
Bio fuel, 80 % TS	100	6	130	100	0.3	0.8	93,0	138200
Coal, 80 % TS	100	6	130	100	0.3	0.8	93,1	139100
Coal, 60 % TS	100	6	130	100	0.3	0.8	92,6	146000
MW, 60 % TS	100	6	130	100	0.3	0.8	92,3	148300
Bio fuel, 60 % TS	100	8	150	2000	0.6	1.6	88,3	178100
Bio fuel, 60 % TS	100	4	110	0	0	0	94,0	126100
Bio fuel, 80 % TS	100	8	150	2000	0.6	1.6	89,1	166500
Bio fuel, 80 % TS	100	4	110	0	0	0	95,6	118500
Bio fuel 40 % TS	100	8	150	2000	0.6	1.6	86,3	206847
Bio fuel 40 % TS	100	4	110	0	0	0	94,0	144894

An uncertainty budget, using GUM principles, gives a maximum uncertainty in the plant performance calculation of 2 %. The uncertainty of the flue gas flow is using the same principle below 7 %. In this case uncertainties documented in CEN standards for solid fuels, and the oxygen content in the flue gas have been used. The dominating uncertainty factors are the carbon and the hydrogen content in the fuel, the heating value of the fuel and the oxygen content in the flue gas.

An uncertainty budget based on such an approximated plant efficiency gives a lower uncertainty, even if an uncertainty as high as 2 % is used for the efficiency and an uncertainty as high as 6 % for the fuel factor.

However, in this example, an uncertainty below 5 % is expected. The reason for this is that there is a number of chemical and physical connections between the parameters that a normal uncertainty budget does not take into consideration.

Table 4.5 shows an uncertainty analysis conducted according to the GUM for a biomass fired plant in which the thermal input is calculated from the boiler efficiency.

Table 4.5 Component uncertainties based on EN 12952-15 and the GUM

Numeric GUM

Parameter:	V_{God}	Q_N	O_2 flue gas	Plant performance
Unit:	m^3n/kg fuel	MW	vol % dg	%
Measured value:	0,265	100,00	8,00	90,50
Relative error	2,0%	2,0%	0,0%	1,0%
Absolute error	0,01	0,000	0,000	1
Sensitivity	2,82	2,82	1,73	1,73
Contribution	0,01	0,71	0,00	1,10
V_{God}	0,265	0,27	0,3	0,3
Q_N	100,000	100,0	100,7	100,0
O_2 flue gas	8,000	8,0	8,0	8,0
Plant performance	90,500	90,5	90,5	91,6
flue gas flow	170285	173771	171492	170285
Uncertainty	4,95%	3486,36	1207,69	0,00
$(\Delta)^2$	17793750	12154704	1458523	0
uncertainty amount		68,3%	8,2%	0,0%

In both the output and input based approaches, the uncertainties of the fuel analysis are fundamental to the accuracy of the flue gas flow calculation. The uncertainties associated with fuel standards cover: fuel sampling; sample preparation and analysis; determination methods for C, H, N, O, S, Cl, water, ash and heating value. In some cases deviant results of flue gas calculations can be explained by differences in the standards used. Sampling and preparation of fuel samples from mixed fuels can lead to deviant results since the elementary composition and heating values are derived from slightly different samples of mixed fuel, i.e., the fuel samples are not fully representative. This aspect is considered further in Chapter 6.

Primary conclusions regarding the uncertainty of the indirect method for biomass fired heating plant are:

- Use of EN 12952-15 to calculate the thermal input leads to an uncertainty below 2% for a normal bio fuel. The plant performance can with very good accuracy be estimated from for example the flue gas temperature, oxygen content in the flue gas etc. This method leads to a lower uncertainty when compared with a detailed uncertainty budget based on the input data used in the full performance equations given in EN 12952-15.
- Use of EN 12952-15 to calculate the flue gas flow leads to an uncertainty below 7% for a normal bio fuel, but it will be a little higher if waste or recovered fuels are used. If the fuel factor calculation is based on the empirical heating value approach then the uncertainty will be lower.
- The main parameter to affect the fuel factor is the fuel moisture content but a measurement error as high as 20% water content only affects the fuel factor by a maximum of about 10%. Even accounting for this, the uncertainty of the flue gas flow is lower than 6% for a heating plant.
- If the moisture content in the fuel is determined during, for example, a parallel measurement, the uncertainty using the fuel factor is reduced and in most cases the total uncertainty will be below 5%.
- Calculation of the dry flue gas flow is an advantage for calculating mass emissions required by the IED.
- The use of the fuel factor principle can also be used for a variety of waste fuels, with acceptable uncertainty levels, especially if V_{God} is based on the empirical heating value approach.
- The components that most affect the uncertainty using EN 12952-15 is the carbon and the hydrogen content in the fuel, the CV value and the oxygen content in the flue gas
- The components that most affects the uncertainty using the fuel factor methods is the fuel factor, the oxygen content in the flue gas and plant performance.

5 CALCULATIONS BASED ON FUEL HEATING VALUE; INPUT BASED APPROACH

5.1 Using the input based approach for oil and gas

The stoichiometric dry flue gas flow rate (m^3/s) is determined from the multiplication of the energy consumption (MW) by a fuel factor (m^3/MJ).

Energy consumption

For gas and liquid fuels, the energy consumption, P_{th} (MW) can be determined directly from the metered fuel consumption, m_F (kg/s) and the measured or supplied net calorific value, $H_{(N)}$ (MJ/kg).

$$P_{\text{th}} = m_F H_{(N)}$$

Volumetric units can be used for flow and CV provided that the volume units and calorific value are referenced to the same temperature and pressure.

Quality assured metering and calorific value determination has an estimated worst case uncertainty of $\pm 1.6\%$ at 95% confidence for large installations under the EU Emissions Trading Scheme Monitoring & Reporting Guidelines although lower values can be used if justified. This uncertainty is the combined allowable maximum uncertainty of the activity data (fuel consumption with metering to $\pm 1.5\%$) and the calorific value (heating value determination to $\pm 0.5\%$).

Fuel factor

Natural Gas

The fuel factor for gaseous fuels can be determined from a molar balance knowing the fuel constituents, as described in EN 12952-15 (§ 8.3.4.2.2). Figure 5.1 shows the fuel factor calculated from composition, plotted against net heating value, for a range of simulated natural gas compositions, obtained by varying the nitrogen and propane content added to methane. The straight line fit is in very close agreement with the empirical formula from EN 12952-15 described in Section 2.1 above.

Since natural gas is most often metered volumetrically, it can be more convenient to calculate the flue gas per unit of fuel volume from the volumetric NCV (MJ/m^3 at 273.15K and 101.325 kPa). This transformation is shown in Figure 5.2, noting that the relationship is equivalent to that currently specified in Holland: $V_{\text{God}} = 0.199 + 0.234 H_{(N)}$.

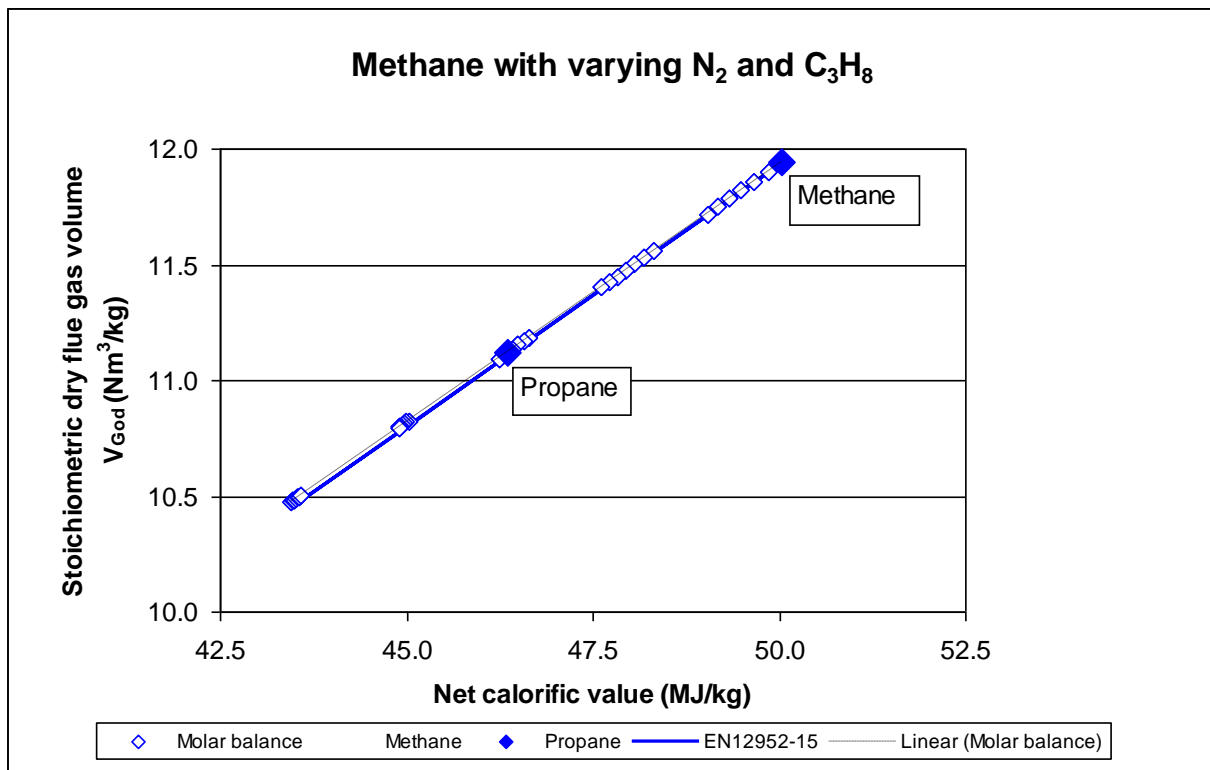


Figure 5.1 Exact calculation of fuel factor from a molar balance (mass specific)

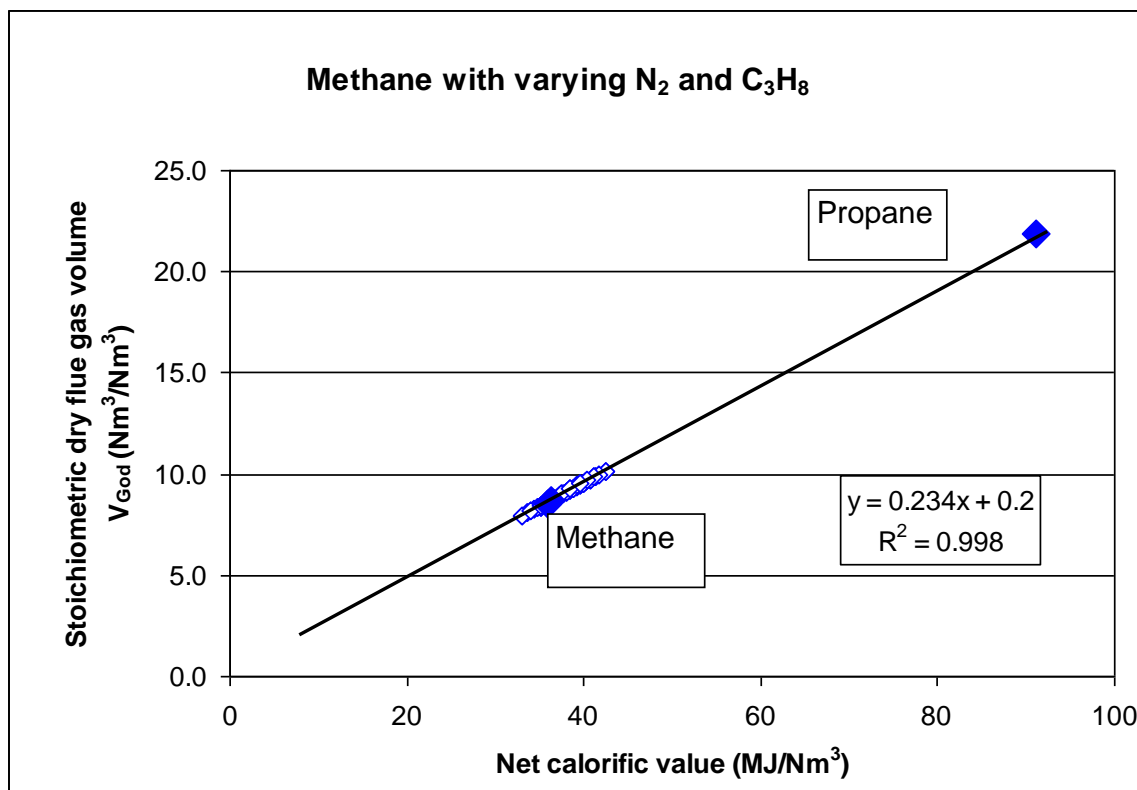


Figure 5.2 Exact calculation of fuel factor from a molar balance (volume specific)

Figure 5.1 spans the expected range of natural gas compositions under the proposed European supply standard EASEE-Gas with parameters specified in Table 5.1.

The molar balance approach used here assumes ideal gas behaviour. Deviations due to non-ideality are very small for the lighter hydrocarbon components and do not have a significant influence on stack flow calculations for natural gas. The EN12952-15 correlation is based on the net calorific value in MJ/kg and this quantity is unaffected by non-ideality. The correlation holds over a much wider range of gas quality and is accurate for pure light hydrocarbon components. Based on an analysis of differences - between the exact and empirical calculations - the uncertainty related to the use of the empirical correlation is estimated to be 0.25% at 95% confidence. However, for non-standard fuel gas, it is recommended that a full calculation check is performed, based on the expected fuel composition, prior to using the empirical formulation.

Table 5.1 EASEE-Gas specification

Parameter	Unit	Min	Max
Wobbe Index	MJ/m ³ (See Note 1)	47	54
Relative Density	m ³ /m ³	0.555	0.70
Total Sulphur	mg/m ³	-	30
Hydrogen Sulphide (H ₂ S) + Carbonyl Sulphide (COS)	mg/m ³	-	5
Mercaptans (R-S-H) (quoted as Sulphur)	mg/m ³	-	6
Oxygen	mole %	-	0.01
Carbon Dioxide	mole %	-	2.5
Water Dew Point	°C at 70 Bar A	-	- 8
Hydrocarbon Dew Point	°C at 1 to 70 Bar A	-	- 2
Hydrogen			Insignificant (See Note 2)

Figure 5.3 shows the EASEE-Gas specification plotted on a calorific value/relative fuel density basis and also shows how the use of propane and nitrogen is used to simulate the gas quality variations within this window.

For the reasons established earlier, the energy specific fuel factor is less variable than a mass specific fuel factor. For natural gas, defined in the IED as naturally occurring gas with a methane content higher than 80%, it is appropriate to use a constant fuel factor of 0.240 m³/MJ (0%O₂, dry 273.15K, 101.325 kPa). The gas fuel factor is appropriate for Group H natural gas (EN 437:2003) provided that this is also natural gas as defined in Directive 2010/75/EU on industrial emissions (integrated pollution prevention and control) in which the methane content is higher than 80%.

Based on an analysis of differences - between the exact and fixed factor calculations, for the range of gas compositions considered above, the expanded uncertainty related to the use of a fixed fuel factor is estimated to be 0.5% at 95% confidence. This increases to 0.7% if the additional uncertainty associated with the net calorific value determination is conservatively assumed to also be 0.5%.

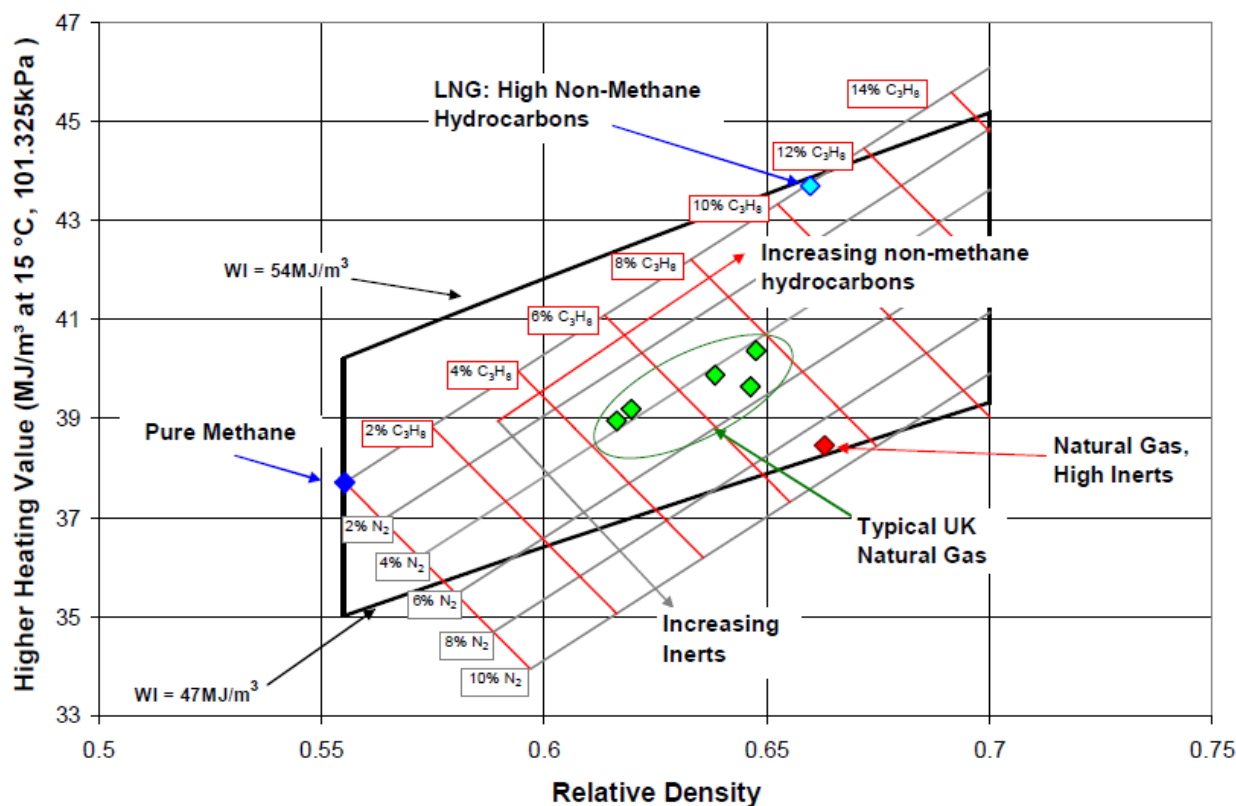


Figure 5.3 EASEE-Gas specification and fuel gas composition mapping

Fuel oil

Since fuel oil is not heavily used in the power industry, when compared with coal and natural gas, the analysis of fuel factors is correspondingly less detailed. Although fuel oil is comprised of a range of complex hydrocarbon compounds, the properties of a given fuel oil grade are controlled within narrow bounds under standard specifications. However, the grading of the fuel oils used in the power industry varies from country to country:

UK classification (BS 2869):

- Light Fuel Oil (E)
- Medium Fuel Oil (F)
- Heavy Fuel Oil (G)

French classification (AFNOR):

- Fioul Lourd TBTS
- Fioul Lourd BTS
- Fioul Lourd HTS

Russian classification (GOST- 10585-99):

- M-40
- M-100

US classification (ASTM D396-80):

- N°5 Fuel Oil
- N°6 Fuel Oil

Most classifications are based on viscosity, although the French heavy oil classification above is based primarily on total sulphur content. Density is another very important parameter from which many of the fuel properties can be calculated.

However, lighter fuels are also fired in the power industry, for example, gas oil (industrial diesel) as a secondary back-up fuel at gas turbine installations.

The fuel factor can be determined from an ultimate analysis using the same formula as for coal (Section 2.1, Eqn. 1). For gas oil and light, medium and heavy fuel oils, the fuel factor can be determined from standard oil analyses [Rose and Cooper, Technical Data on Fuel, Scottish Academic Press, 1977]. Table 5.2 shows the mass specific (V_{God}) and energy specific (S) fuel factors calculated using these standard values of composition and NCV. The mass specific fuel factor does not vary substantially ($10.25 \text{ m}^3/\text{kg} \pm 0.25 \text{ m}^3/\text{kg}$ or $\pm 2.5\%$ relative). The energy specific fuel factor, S, is less variable, as expected, at $0.247 \text{ m}^3/\text{MJ} \pm 1.5\%$ relative. However, the value of S calculated from the EN 12952-15 empirical formula is even less variable and about 1.2% lower than the handbook values would suggest ($0.244 \text{ m}^3/\text{MJ}$). Three heavy fuel oil analyses have been examined and these yield an S value of $0.248 \text{ m}^3/\text{MJ}$ as shown in Table 5.2, again slightly higher than EN 12952-15.

Table 5.2 Flue gas volume of fuel oil (handbook fuel properties)

Analysis	Gas Oil	LFO	MFO	HFO
C	86.1%	85.6%	85.6%	85.4%
H	13.2%	11.7%	11.5%	11.4%
O	0.0%	0.0%	0.0%	0.0%
N	0.0%	0.1%	0.2%	0.2%
S	0.7%	2.5%	2.6%	2.8%
Cl	0.0%	0.0%	0.0%	0.0%
Ash	0.0%	0.1%	0.2%	0.2%
Moisture	0.0%	0.0%	0.0%	0.0%
Total	100.0%	100.0%	100.0%	100.0%
$V_{\text{God}} (\text{Nm}^3/\text{kg})$	10.45	10.15	10.11	10.08
NCV (MJ/kg) book	42.80	41.10	40.80	40.50
S (Nm^3/MJ) calculated	0.244	0.247	0.248	0.249
S (Nm^3/MJ) EN 12952-15	0.242	0.244	0.244	0.244

Table 5.3 Flue gas volume of heavy fuel oil (measured fuel properties)

Analysis	HFO-1	HFO-2	HFO-3
C	87.0%	87.9%	87.0%
H	11.2%	10.9%	11.2%
O	0.3%	0.1%	0.2%
N	0.6%	0.2%	0.6%
S	0.8%	1.0%	1.0%
Cl	0.0%	0.0%	0.0%
Ash	0.0%	0.0%	0.0%
Moisture	0.0%	0.0%	0.0%
Total	100.0%	100.0%	100.0%
V_{God} (Nm ³ /kg)	10.12	10.13	10.11
NCV (MJ/kg) measured	40.79	40.75	40.81
S (Nm ³ /MJ) calculated	0.248	0.248	0.248
S (Nm ³ /MJ) EN 12952-15	0.244	0.244	0.244

The US EPA factor for oil is 0.244 m³/MJ, based on an average GCV:NCV ratio of 0.94, and this is consistent with EN 12952-15. However, this is an under-estimate for Heavy Fuel Oil and so the EN 12952-15 correlation should be used for light fuel oils only. The use of either a fixed factor of 0.244 m³/MJ or the correlation for light fuel oils is appropriate and delivers a value with an uncertainty of $\pm 1.5\%$, assuming that the uncertainty of the CV determination is 0.325% at 95% confidence (based on ASTM D240-02: Standard Test Methods for Heat of Combustion of liquid hydrocarbon fuels by bomb calorimeter).

A higher stack flow factor of 0.248 m³/MJ is recommended for Heavy fuel Oil and it is recommended that non-standard liquid fuels are evaluated on a case-by-case basis from the fuel analysis which may be based on a commercial fuel specification.

5.2 Uncertainty of the flue gas volume using the input based approach

The uncertainty of a method is a crucial parameter in the decision to choose between different calculation and/or measurement methods. The uncertainty of the calculation method is often substantially better than can be achieved by flue gas flow measurement.

In broad terms, the reference methods used to calibrate flue gas flow meters have an expanded uncertainty up to $\pm 5\%$ based on CEN WG23 validation trials. Assuming that the AMS can be controlled to a similar level, the combined uncertainty is of the order of 7.5% and this represents half of the confidence interval of 15% currently specified in Holland for

stack flow determination. This implies that a calculation approach needs to always have an uncertainty better than about $\pm 7.5\%$.

However, it is shown in Section 5.1 that the uncertainty of the thermal input is circa $\pm 1.6\%$. When this is combined with the fuel factor uncertainty for gas or oil, the combined uncertainty of the input based approach is always lower than $\pm 3.0\%$.

6 VALIDATION OF EN 12952-15 FOR COAL AND BIOMASS

6.1 Vattenfall validation using the ECN Phyllis database for biomass and waste

In Sweden, the most common method to determine the flue gas flow for bio-fuels is the indirect method, described in EN 12952-15. The principles of this are described previously in Section 4. The use of a fuel factor can also be advantageous for very inhomogeneous waste fuels.

In both methods, the fuel factor (m^3/MJ) is multiplied by the net thermal energy input to the plant (MW) and then compensated for the oxygen content in the flue gas (reference or actual depending on requirements). Flue gas flow = $S * P_{th} * 20.94 / (20.94 - O_2)$.

The principle of the indirect method is that P_{th} is determined by the measurement of produced energy and all losses in the system.

$$P_{th} = P_{prod} - P_{heat\ credits} + P_{losses}$$

P_{losses} = P losses in ash + P radiation losses + P enthalpy losses + P losses in unburned components (such as CO) as discussed earlier. The equation is very complex since the flue gas flow is used to calculate the losses in flue gas enthalpy and losses in unburned components in the flue gas. The calculation steps required to determine the thermal input in this way are described in EN 12952-15. In this standard there are also separate methods to calculate the fuel factor from fuel composition, presented earlier as Equation 1:

$$V_{God} = 8.8930 \gamma_C + 20.9724 \gamma_H + 3.3190 \gamma_S - 2.6424 \gamma_O + 0.7997 \gamma_N \quad (\text{m}^3/\text{kg fuel})$$

(8.3-60 in EN 12952-15)

$H_{(N)}$ = Net (lower) heating value of fuel (MJ/kg)

S = Fuel factor = $V_{God} / H_{(N)}$ (m^3/MJ)

γ = mass fraction in the as received fuel (-)

Table 6.1 gives typical fuel compositions of important fuels and the values of V_{God} , $H_{(N)}$ and S . All fuel data are from the Phyllis data base, recalculated to 0% fuel moisture content (dry substance). Note that the mass fractions are given as percentages in the table and must be divided by 100 prior to use in the above equation.

Table 6.1 Calculation of the Fuel Factor using measured $H_{(N)}$ values

Fuel type	C (w %)	H (w %)	O (w %)	N (w %)	S (w %)	Ash (w %)	V_{God} (m ³ /kg)	$H_{(N)}$ (MJ/kg)	Fuel Factor _f (m ³ /MJ)
Bark average	52.30	6.00	40.00	0.20	0.00	1.60	4.85	19.19	0.253
Wood pellets	50.10	6.07	43.20	0.09	0.01	0.50	4.59	18.61	0.247
Forest residue	50.30	4.59	40.00	1.03	0.11	4.00	4.39	19.17	0.229
Waste wood	50.50	5.95	35.50	0.53	0.06	7.40	4.81	-	-
Finnish peat	54.40	5.90	35.10	1.10	0.15	4.20	5.16	23.32	0.221
Barley	46.80	5.53	41.90	0.41	0.06	4.90	4.22	17.56	0.240
Brown coal German	63.90	4.97	24.50	0.57	0.48	4.50	6.10	24.02	0.254
Mixed waste wood	50.70	5.91	40.10	1.68	0.06	1.40	4.70	16.00	0.294
Municipal solid waste	33.90	4.60	22.40	0.70	0.40	38.00	3.41	12.10	0.282
MSW plastic Netherlands	81.10	13.33	0.00	0.11	0.01	4.40	10.01	39.18	0.255

A problem with combining a calculated stoichiometric flue gas flow from the elementary composition, V_{God} , with the NCV, $H_{(N)}$, is that the composition and heating value can be measured for fuel samples with different compositions. An error in either the elementary components or $H_{(N)}$ will affect the flue gas flow.

One alternative is to also calculate the $H_{(N)}$ value from the fuel composition using well established reference data for the heat of combustion of individual elements. One formula that can be used for such calculation is the Milne's formula which is described in the Phyllis database and also used, for example, in the Swedish organization "Varmeforsks" advanced fuel data base. This is taken originally from work conducted in the United States (Coal Conversion Systems Technical Data Book - US DOE Report DOE/FE/05157-5, 1984). From these early studies, the equation is bias free for coal with a standard deviation between calculated and measured values of 129 Btu/lb, equating to an uncertainty at 95% confidence of 0.59 MJ/kg) or 2.35% relative at a CV of 25 MJ/kg. Most of this uncertainty is attributed to the uncertainty of determining the composition. Assuming equivalent performance for biomass fuels it would be reasonable to expect a calculated and measured CV to be within 5%.

Milne's formula is based on the dry fuel elementary composition:

$$H_{(G)} = 34.1 \gamma_C + 132.2 \gamma_H + 6.86 \gamma_S - 12 \gamma_O - 12 \gamma_N - 1.53 \gamma_{Ash}$$

With $H_{(G)}$ = Gross calorific value and γ is the mass fraction.

This can be converted to an as received basis, as before, by multiplying by $(1 - \gamma_{H_2O})$.

To correct $H_{(G)}$ to $H_{(N)}$ the following standard formula is used, noting that this is also used to calculate a measured GCV to an NCV. Note that the formulas used to calculate for example $H_{(G)}$ to $H_{(N)}$ as received is included in the EN standards of solid fuels. A list of solid fuel standards is included in appendix II.

$$H_{(N)} = H_{(G)} - 21.22 \gamma_H - 0.08 (\gamma_O + \gamma_N) - 2.4425 \gamma_{H_2O}$$

In Table 6.2 the calculated, rather than measured, $H_{(N)}$ values have been used to calculate the additional parameters. Note that the mass fractions are given as percentages in the table and must be divided by 100 prior to use in the above equations.

Table 6.2 Calculation of Fuel factor using $H_{(N)}$ values, calculated by Milnes equation

Fuel type	C (w %)	H (w %)	O (w %)	N (w %)	S (w %)	Ash (w %)	$V_{G_{od}}$ (m ³ /kg)	$H_{(N)}$ (Milne) (MJ/kg)	$V_{G_{od}}/H_{(N)}$ (m ³ /MJ)
Bark average	52.3	6.0	40.0	0.2	0.0	1.6	4.86	19.61	0.247
Wood pellets	50.1	6.1	43.2	0.1	0.0	0.5	4.60	18.58	0.247
Forest residue	50.3	4.6	40.0	1.0	0.1	4.0	4.40	17.24	0.255
Waste wood	49.0	5.8	37.3	0.8	0.1	6.9	4.60	19.36	0.248
Finnish peat	53.5	5.8	32.0	2.0	0.3	7.5	5.16	20.67	0.250
Barley	46.8	5.5	41.9	0.4	0.1	4.9	4.23	16.92	0.249
Brown coal German	63.9	5.0	24.5	0.6	0.5	4.5	6.10	24.24	0.252
Mixed waste wood	50.7	5.9	40.1	1.7	0.1	1.4	4.71	18.79	0.250
Municipal solid waste	47.6	6.0	32.9	1.2	0.3	12.0	4.65	13.32	0.256
MSW plastic Netherlands	81.1	13.3	0.0	0.1	0.0	4.4	10.01	42.37	0.236

It is evident that the S factor ($V_{god}/H_{(N)}$) is very similar for all dry fuels, noting that the factor for pure carbon is also similar at 0.261. The S factors for all solid fuels (dry fuels), with an ash content below about 20%, always lie within a narrow range. In EN 12952-15, an alternative

equation to calculate V_{God} that takes this problem into consideration is described later in this chapter.

However, the fuel moisture content affects the S factor directly. The S factor will increase if the moisture content increases since additional fuel energy (and therefore additional dry flue gas) is required to evaporate the moisture in the fuel. In Tables 6.3 and 6.4, V_{God} , $H_{(\text{N})}$ and S are calculated for the same fuels as above but with different moisture contents.

Table 6.3 The effect of changes in moisture content on V_{God} and $H_{(\text{N})}$

Fuel type\Moisture content	V_{God} (m ³ /kg fuel)				$H_{(\text{N})}$ (MJ/kg fuel)			
	0 %	20 %	40 %	60 %	0 %	20 %	40 %	60 %
Bark average	4.85	3.88	2.91	1.94	19.61	15.20	10.79	6.38
Wood pellets	4.59	3.67	2.75	1.84	18.58	14.38	10.17	5.97
Forest residue	4.39	3.51	2.63	1.76	17.24	13.30	9.37	5.43
Waste wood	4.81	3.85	2.88	1.92	19.36	15.00	10.64	6.28
Finnish peat	5.16	4.13	3.10	2.06	20.67	16.05	11.43	6.81
Barley	4.22	3.38	2.53	1.69	16.92	13.04	9.17	5.30
Brown coal German	6.10	4.88	3.66	2.44	24.24	18.91	13.57	8.23
Mixed waste wood	4.70	3.76	2.82	1.88	18.79	14.54	10.30	6.05
Municipal solid waste	3.41	2.73	2.04	1.36	13.32	10.17	7.02	3.86
MSW plastic Netherlands	10.01	8.01	6.01	4.00	42.37	33.41	24.45	15.48

Table 6.4 The effect of changes in moisture content on S ($V_{\text{God}}/H_{(\text{N})}$)

Fuel type\Moisture content	Fuel Factor m ³ /MJ fuel			
	0 %	20 %	40 %	60 %
Bark average	0.247	0.255	0.270	0.304
Wood pellets	0.247	0.255	0.271	0.307
Forest residue	0.255	0.264	0.281	0.323
Waste wood	0.248	0.256	0.271	0.306
Finnish peat	0.250	0.257	0.271	0.303
Barley	0.249	0.259	0.276	0.318
Brown coal German	0.252	0.258	0.270	0.296
Mixed waste wood	0.250	0.259	0.274	0.311
Municipal solid waste	0.256	0.268	0.291	0.353
MSW plastic Netherlands	0.236	0.240	0.246	0.259
AVERAGE VALUE	0.249	0.257	0.272	0.308

Table 6.4 shows that the moisture content significantly affects the fuel factor, S. It is therefore important to determine the moisture content in the fuel when comparing parallel flue gas flow measurements with calculated values.

In Figure 6.1 the S factor is compared for 163 different fuels, mostly from the Phyllis data base but with a few additions.

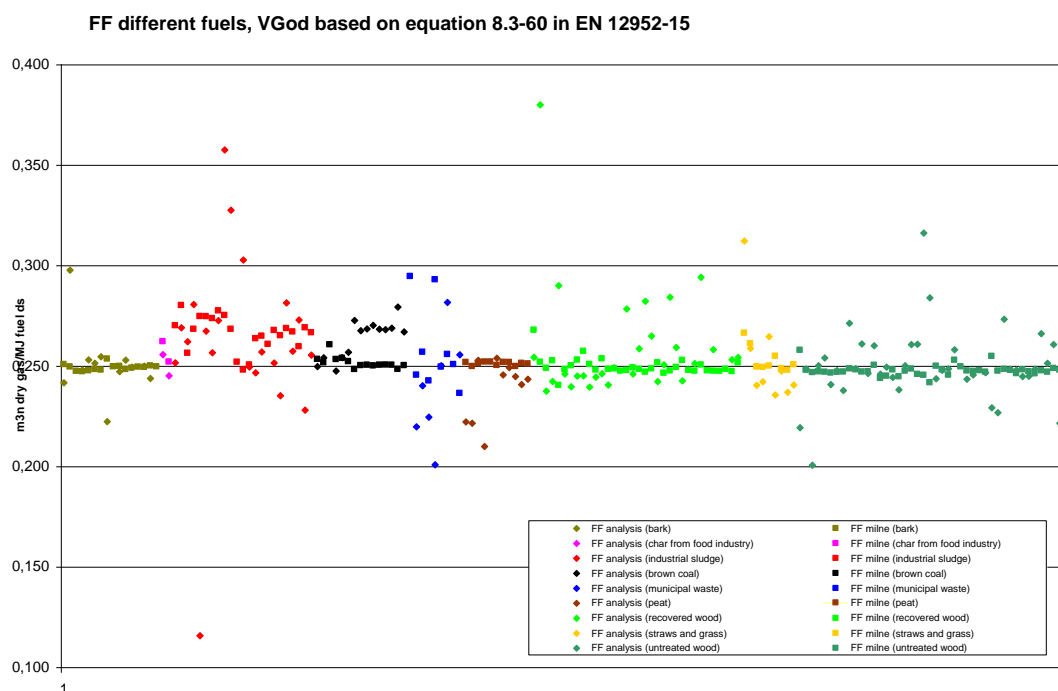


Figure 6.1 Fuel Factor (m^3/MJ), dry fuel, V_{God} is based on 8.3-60 in EN 12952-15

This encompasses the full range of physical forms and biological origins. For example, wood - chips, pellets, fines, residues and briquettes are included but also different source wood types such as ash, oak, birch, spruce, pine, salix, cedar, poplar, larch etc in the untreated wood category. This also applies to the other fuel groupings.

In Figure 6.1 fuel factors based upon both the measured and calculated (Milnes) NCV values have been included since the main problem for many of these fuels is that the $H_{(N)}$ and the elementary composition are measured using different samples, as noted above. Without doubt, the database contains some inconsistent analyses but this can be checked by comparing the measured and calculated NCV values.

The CEN solid fuel standards include the measurement of $H_{(N)}$ by bomb calorimetry and also elemental analysis. There is also, of course, a standard for the preparation of fuels for analysis, a standard for representative sampling, etcetera. However, the use of a calculated $H_{(N)}$ value is also allowed and this can be preferable when applying standards such as EN 12952-15.

Almost all of the observed “outliers” give unrealistic values of the measured $H_{(N)}$ when compared with those calculated from the fuel composition.

The alternative empirical formula in EN 12952-15, linking flue gas volume to NCV, addresses this issue:

$$V_{\text{God}} = -0.06018 * (1 - \gamma_{\text{Ash}} - \gamma_{\text{H}_2\text{O}}) + 0.25437 * (H_{(N)} + 2.4425 \gamma_{\text{H}_2\text{O}})$$

The fuel factor from this calculated V_{God} produces almost identical results for nearly all dry solid fuels as shown in Figure 6.2 and Table 6.5. A very interesting result is that it does not matter if the heating value is measured or calculated by, for example, the Milne equation.

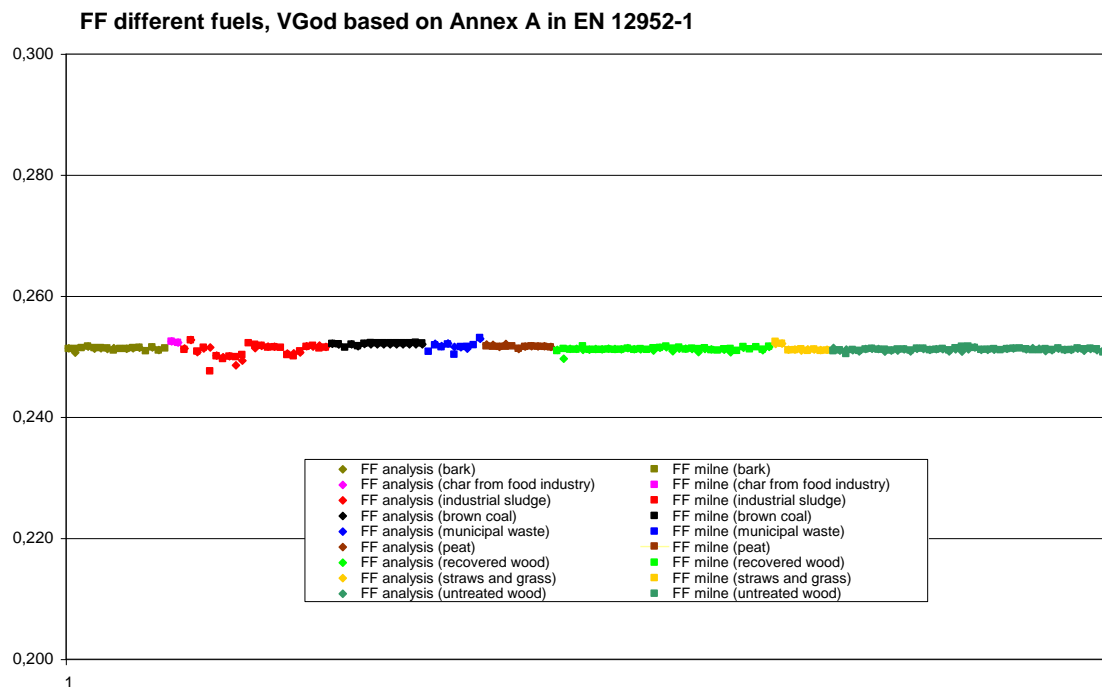


Figure 6.2 Fuel Factor (m^3/MJ), dry fuel, V_{God} is based on Annex A in EN 12952-15

In Table 6.5 the variation in fuel factor is expressed as a min, max and mean value using the two different methods to calculate V_{God} .

Table 6.5 Variation in fuel factor using V_{God} calculated by 8.3-60 or Annex A in EN 12952-15 respectively

	Fuel Factor, S by analysis, V_{God} calculated by 8.3-60	Fuel Factor, S by Milne, V_{God} calculated by 8.3-60	Fuel Factor, S by analysis, V_{God} calculated by Annex A	Fuel Factor, S by Milne, V_{God} calculated by Annex A
	(m^3/MJ fuel)	(m^3/MJ fuel)	(m^3/MJ fuel)	(m^3/MJ fuel)
mean value	0.254	0.252	0.251	0.251
min value	0.116	0.236	0.249	0.248
max value	0.380	0.294	0.253	0.253

The equation in Annex A also takes the moisture content into consideration. For example if the fuel factor for a bio-fuel using the V_{God} equation in Annex A of EN 12952-15 gives the following results, Table 6.6.

Table 6.6 The effect of fuel moisture using Annex A EN 12952-15 to calculate V_{God}

	0%	20%	40%	60%
Fuel Type	(m^3/MJ)	(m^3/MJ)	(m^3/MJ)	(m^3/MJ)
Bark average	0.251	0.259	0.274	0.309
Wood pellets	0.251	0.260	0.275	0.313
Forest residue	0.251	0.260	0.277	0.319
Waste wood	0.251	0.260	0.275	0.311
Finnish peat	0.252	0.259	0.273	0.306
Barley	0.251	0.260	0.278	0.321
Brown coal German	0.252	0.259	0.270	0.297
Mixed waste wood	0.251	0.260	0.275	0.312
Municipal solid waste	0.252	0.264	0.288	0.351
MSW plastic Netherlands	0.253	0.257	0.263	0.277
Average	0.252	0.260	0.275	0.312

If the results in Table 6.4 and Table 6.6 are compared it can be seen that they are very similar and the percentage differences are given in Table 6.7.

Table 6.7 Percentage differences using 8.3-60 of Annex A in EN 12952-15 for fuels with different moisture contents

Fuel Type\	Moisture content in respective fuels			
	0% (% difference)	20% (m ³ /MJ fuel)	40% (m ³ /MJ fuel)	60% (m ³ /MJ fuel)
Bark average	-1.56	-1.57	-1.59	-1.63
Wood pellets	-1.74	-1.74	-1.76	-1.79
Forest residue	1.45	1.43	1.39	1.32
Waste wood	-1.31	-1.34	-1.39	-1.49
Finnish peat	-0.77	-0.79	-0.82	-0.88
Barley	-0.61	-0.63	-0.68	-0.76
Brown coal German	-0.18	-0.20	-0.23	-0.28
Mixed waste wood	-0.33	-0.34	-0.36	-0.39
Municipal solid waste	1.61	1.44	1.14	0.55
MSW plastic Netherlands	-7.11	-7.11	-7.13	-7.16
Average	-1.01	-1.03	-1.06	-1.12

Table 6.7 shows that the influence of the moisture content is almost identical in both methods for calculating V_{God} .

Two other methods to calculate $H_{(N)}$ have also been studied. The first one is developed for bio fuels by Gösta Rosenblad Energiteknik I, 1968, which uses the mass percentages of the fuel components:

$$H_{(N)} = (0.341 \cdot C + 1.245 \cdot H - 0.0985 \cdot O + 0.063 \cdot N + 0.191 \cdot S) - 2.5 \cdot (8.94 \cdot H / 100) - 2.5 \cdot H_2O / 100$$

The other is a published unified calculation method (Channiwalaa, S.A., Parikhb, P.P., 'A unified correlation for estimating HHV of solid, liquid and gaseous fuels', Fuel, 81(8), 1051-1063, 2002) which also uses the mass percentages of the fuel components:

$$H_{(N)} = 0.3491 \cdot C + 1.1783 \cdot H + 0.1005 \cdot S - 0.1034 \cdot O - 0.0151 \cdot N - 0.0211 \cdot A$$

The variation in V_{God} of the four studied methods to calculate the Heating Value is compared in Table 6.8 and 6.9. In Table 6.8, V_{God} has been calculated using 8.3-60 and in Table 6.9 V_{God} according to Annex A.

Table 6.8 Variation in fuel factor using V_{God} calculated by 8.3-60 in EN 12952-15

	Fuel Factor, measured NCV	Fuel Factor, NCV from Milne	Fuel Factor, NCV from unified equation	Fuel Factor, NCV from Rosenblad
	(m ³ /MJ fuel)	(m ³ /MJ fuel)	(m ³ /MJ fuel)	(m ³ /MJ fuel)
mean value	0.254	0.252	0.249	0.242
min value	0.116	0.236	0.241	0.231
max value	0.380	0.294	0.291	0.259

Table 6.9 Variation in fuel factor using V_{God} calculated by Annex A in EN 12952-15

	Fuel Factor, measured NCV	Fuel Factor, NCV from Milne	Fuel Factor, NCV from unified equation	Fuel Factor, NCV from Rosenblad
	(m ³ /MJ fuel)	(m ³ /MJ fuel)	(m ³ /MJ fuel)	(m ³ /MJ fuel)
mean value	0.251	0.251	0.251	0.251
min value	0.249	0.248	0.248	0.249
max value	0.253	0.253	0.253	0.253

As expected, the variation in heating value from the different estimation methods does not affect the results if the Annex A method is used to calculate V_{God} .

6.2 KEMA dataset for coal and biomass

This section details the validation of the EN 12952-15 standard in relation to the KEMA database for coal and biomass. The relationship between the stoichiometric dry flue gas volume (V_{God}) and the dry fuel calorific value ($H_{(\text{N})\text{d}}$) is evaluated based on both fuel composition and the empirical heating value approach.

6.2.1 Coal

The analytical data of over 39 coal samples are recorded in the KEMA dataset. The elemental concentration and calorific value are determined for 28 of these samples (KEMA, 2004). Past research already showed a good relationship between V_{God} (based on composition) and $H_{(\text{N})\text{d}}$. In this sub-section, the formulas of the EN12952-15 standard are used to validate the calculation of stoichiometric dry flue gas volume using the KEMA dataset and the Milne formula is again used for theoretical validation.

The EN 12952-15 standard describes two methods. The Milne formula is used as validation method:

- EN 12952-15 fundamental: based on fuel composition
- EN 12952-15 empirical: based on heating value
- Milne: calculation of net caloric value to support the empirical method.

Figure 6.3 shows the relationship of V_{God} and $H_{(\text{N})\text{d}}$ from the KEMA coal dataset, which matches well with both formulas from the EN 12952-15 standard. The V_{God} of the samples were calculated according to the stoichiometric method. Thereafter the V_{God} of the samples were plotted against $H_{(\text{N})\text{d}}$ and a linear regression line was plotted. A second regression line was plotted according to the EN empirical method and this matches very well the regression line for the stoichiometric calculation.

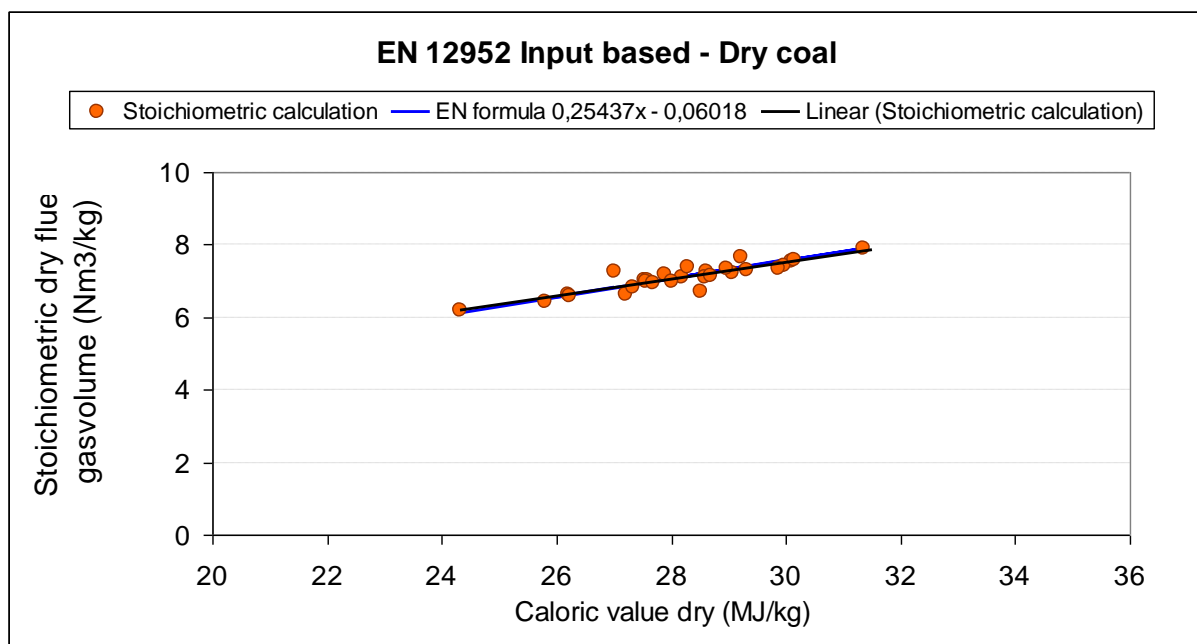


Figure 6.3 Relation between stoichiometric dry flue gas volume (V_{God}) plotted against dry net calorific value ($H_{(\text{N})\text{d}}$) of dry coal according to EN 12952-15 standard (fuel composition method) and the regression line of the EN 12952-15 empirical formula

It is interesting to determine if the EN 12952-15 methods and the Milne formula agree for the KEMA dataset shown in Figure 6.3 since this would enable validation of the EN 12952-15 methods using a calculated $H_{(\text{N})\text{d}}$. This is shown in Figure 6.4. The V_{God} of the samples were calculated according to the fuel composition method with $H_{(\text{N})\text{d}}$ calculated by the

Milne formula. A linear regression line is plotted for the samples points of the Milne calculation and a regression line is plotted from the EN heating value method. The regression lines agree very well, although, for $H_{(N)d}$ below 26 MJ/kg, the deviation increases.

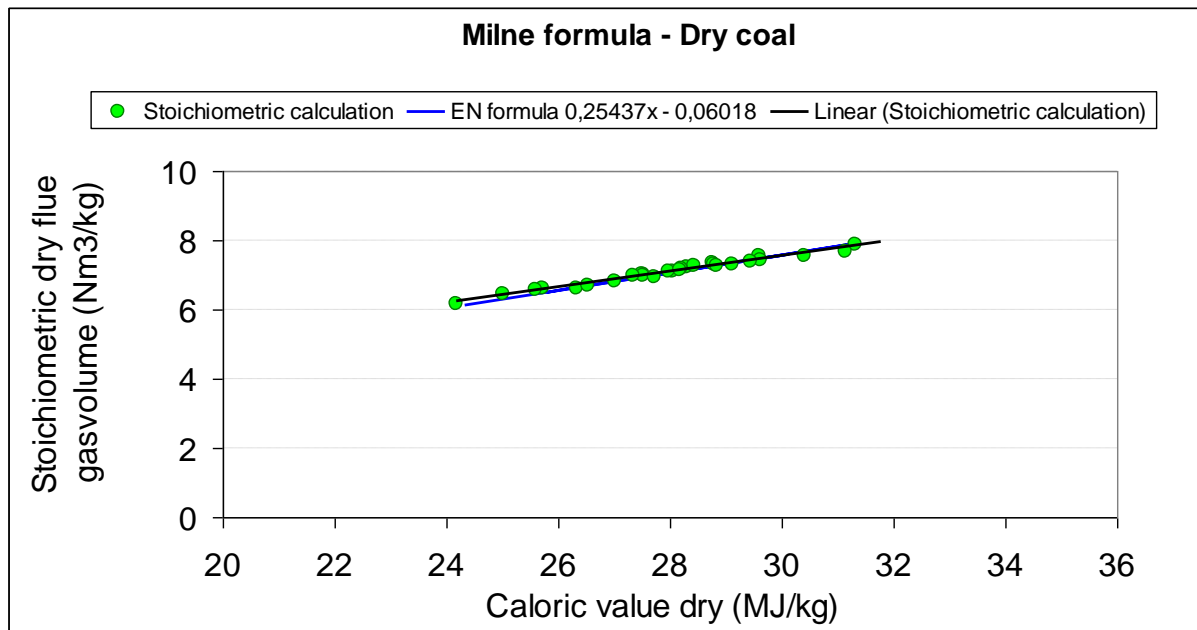


Figure 6.4 Relation between stoichiometric dry flue gas volume ($V_{G_{od}}$) plotted against the calculated dry calorific value ($H_{(N)d}$) of dry coal according to EN 12952-15 standard (stoichiometric method) and Milne formula

6.2.2 Biomass

The analytical data for a wide range of biomass samples are recorded in the KEMA dataset. The elemental composition and calorific value are determined¹ for 85 samples (KEMA, 2001). A relation between stoichiometric $V_{G_{od}}$ (based on fuel composition) and $H_{(N)d}$ is also determined for these secondary solid fuels which will be referred to as biomass.

The EN 12952-15 standard describes two methods. The Milne formula is used as validation method:

- EN 12952-15 fundamental: based on fuel composition
- EN 12952-15 empirical: based on heating value
- Milne: calculation of net calorific value to support the empirical method.

¹ Numbers of samples where required data is complete

Figure 6.5 gives the relationship between V_{God} and $H_{(\text{N})\text{d}}$ for the KEMA biomass dataset and shows that the two EN 12952-15 methods agree perfectly, as shown by the two regression lines which are over-laid in the plot. The individual V_{God} data points were calculated according to the stoichiometric (fuel composition) method. The outcome of calculating the fuel factor S in m^3/MJ is the same for both methods. In this case, the samples are mostly in the range from 10 to 20 MJ/kg $H_{(\text{N})\text{d}}$.

Interestingly, the biomass samples in general have different compositions (when compared with coal) but still follow the same linear regression line. Reason for this can be found in the stoichiometric composition of biomass. In general, biomass contains more oxygen and less carbon than for example coal samples. Carbon is responsible for a higher and oxygen for a lower V_{God} . Apparently this difference in composition leads to a relatively similar decline in V_{God} as it does in $H_{(\text{N})\text{d}}$. In conclusion, this results in the same regression line as the EN empirical formula.

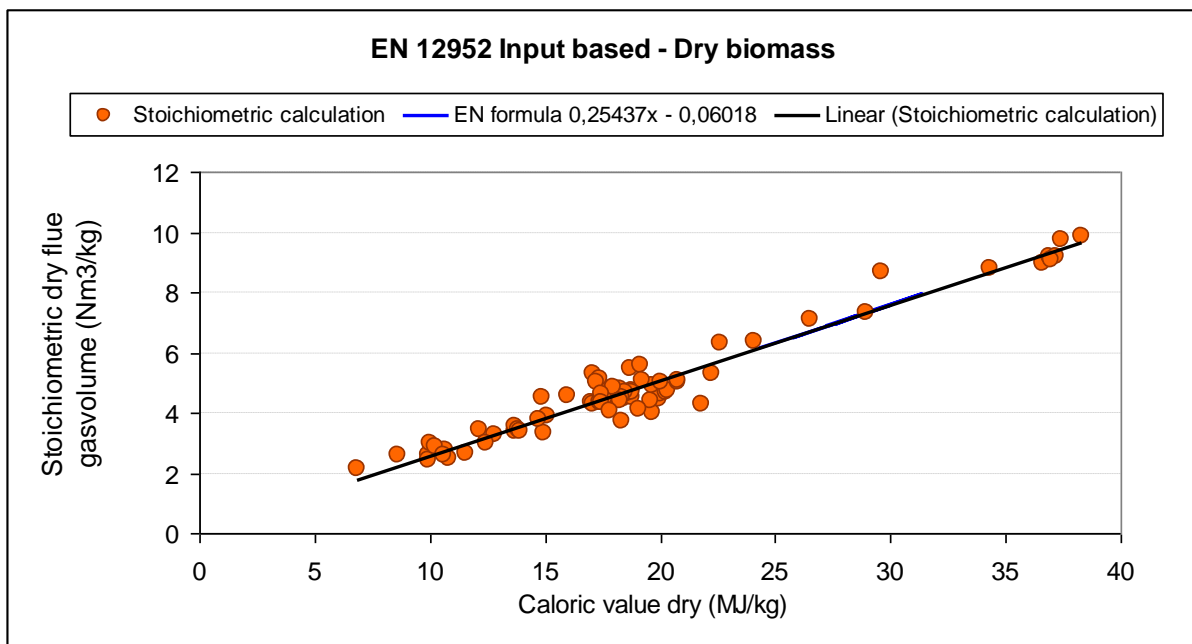


Figure 6.5 Relation between stoichiometric dry flue gas volume (V_{God}) plotted against dry calorific value ($H_{(\text{N})\text{d}}$) of dry biomass according to EN 12952-15 standard (stoichiometric method) and regression line of the EN 12952-15 empirical formula

Using the Milne formula to validate the EN standard according to Milne's theoretically calculated $H_{(N)d}$ does not correlate well for biomass with high heating values as shown in Figure 6.6. A linear regression line was plotted from the sample points of the Milne calculation and a regression line from the EN formula. The deviation rapidly increases between the two regression lines starting from a low to a high $H_{(N)d}$. The Milne formula is designed for coal samples, where the EN formula is designed for all kinds of solid fuels. This means that biomass samples with a high calorific value are more sensitive to a larger uncertainty.

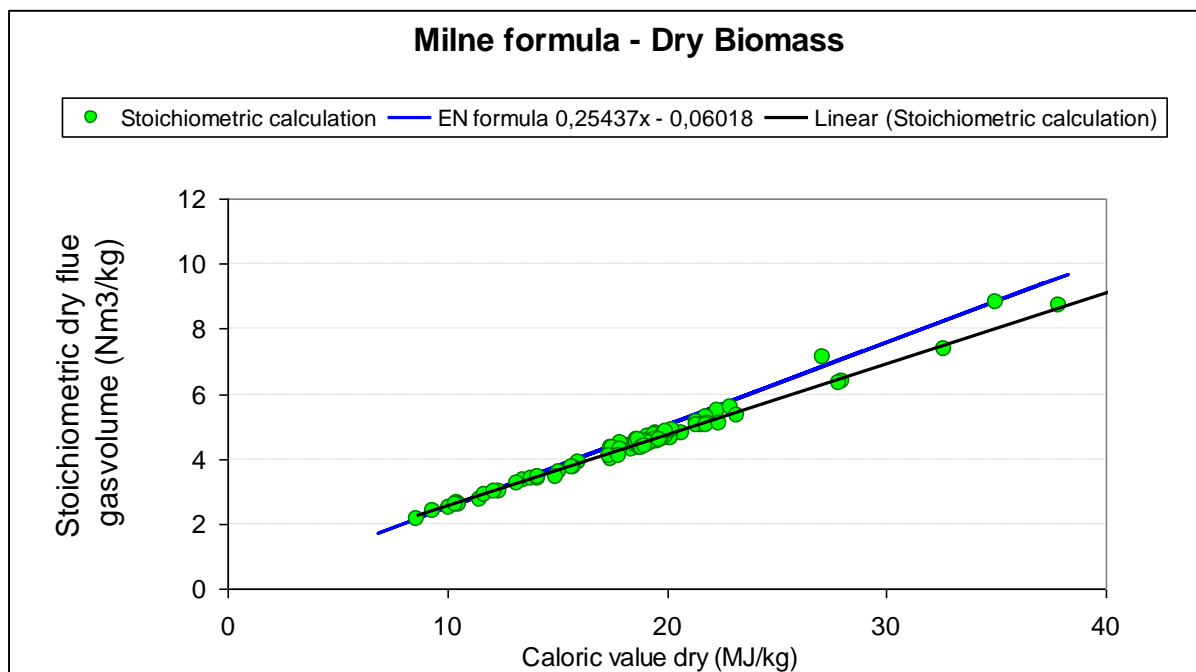


Figure 6.6 Relation between stoichiometric dry flue gas volume (V_{G0d}) plotted against the calculated dry calorific value ($H_{(N)d}$) of dry biomass according to EN 12952-15 standard (stoichiometric method) and Milne formula

6.2.3 Biomass and coal

A relation between stoichiometric dry flue gas volume and dry calorific value matches the linear equation of the EN empirical formula. The dry flue gas volume can be very well calculated for various coal/biomass compositions using both equations from EN 12952-15. This is illustrated in Figure 6.7 for the complete dataset of coal and biomass.

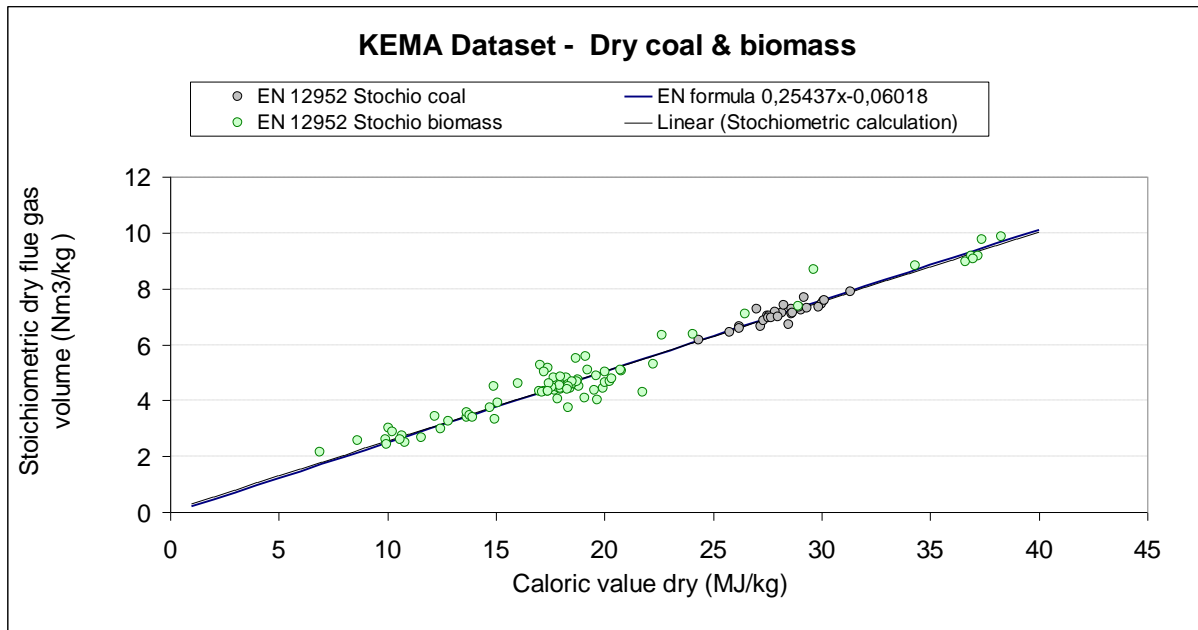


Figure 6.7 Relation between stoichiometric dry flue gas volume (V_{God}) plotted against dry calorific value ($H_{(\text{N})\text{d}}$) of dry coal and biomass according to EN 12952-15 standard (stoichiometric method) and regression line of the EN 12952-15 empirical formula

6.3 E.ON validation on coal

Similar calculations have been performed using a database of 171 internationally traded hard coal samples (including fuel moisture). Figure 6.8 shows V_{God} calculated from fuel composition plotted against the measured NCV.

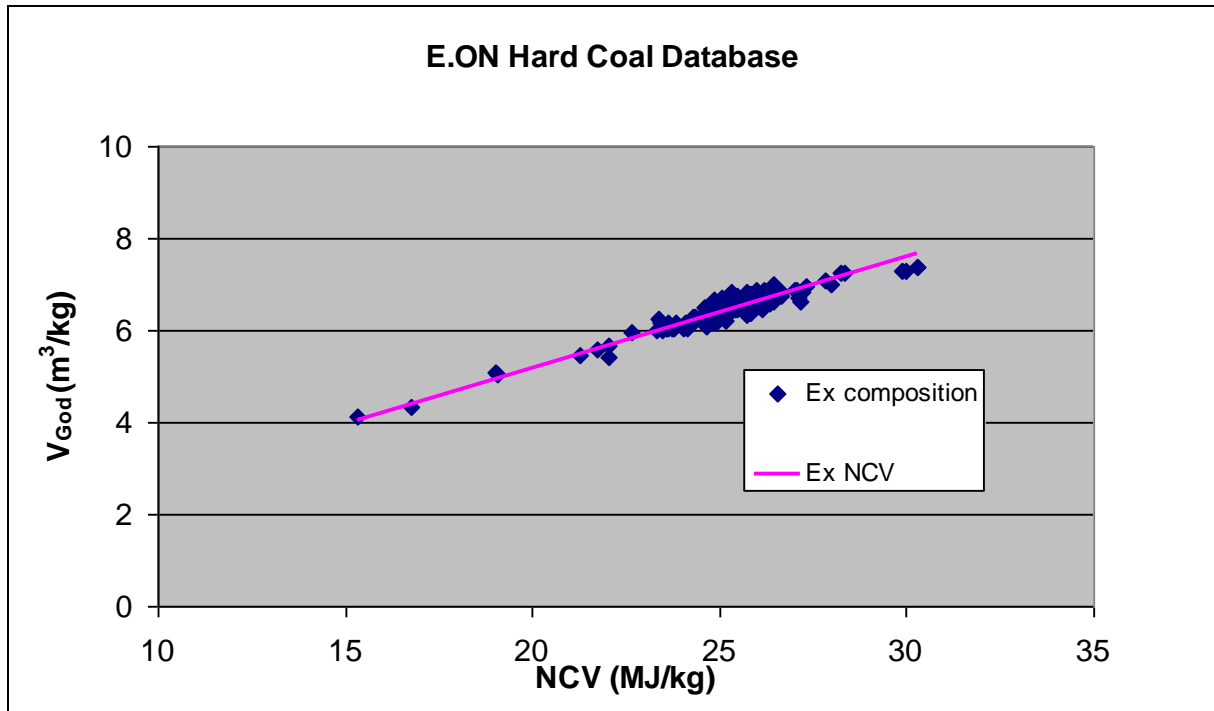


Figure 6.8 V_{God} calculated from composition and measured NCV for 171 hard coal samples

Figure 6.9 shows the same data correlated against a calculated NCV (Milne) and the scatter is much reduced. This simply infers that there is some inconsistency between the elemental composition and the NCV. In fact, the scatter is most likely to be caused by the uncertainty in the determination of composition, rather than the uncertainty in the NCV determination, and it is therefore generally better to base a flue gas calculation on NCV rather than fuel composition.

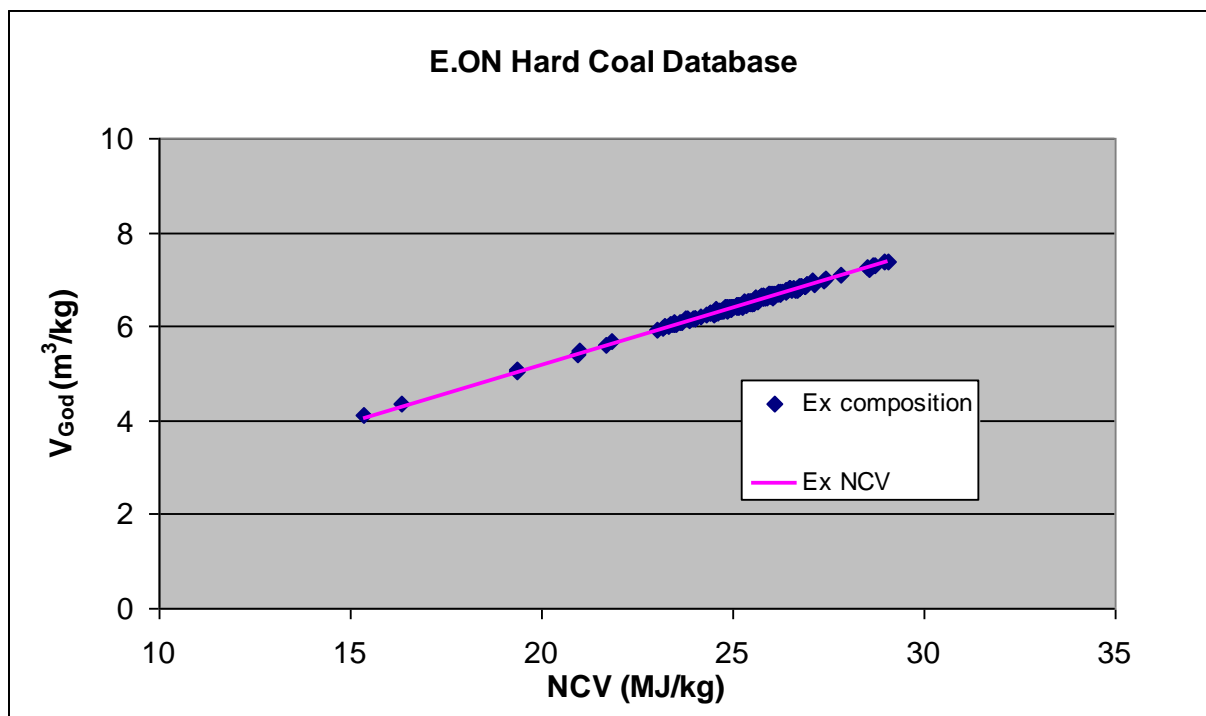


Figure 6.9 V_{God} calculated from composition and calculated NCV for 171 hard coal samples

When each data point is divided by the associated NCV, the average fuel factor, S , is $0.256 \text{ m}^3\text{/MJ}$ - the same as that determined from the KEMA database and within 0.2% of the US EPA fixed value assuming an average GCV:NCV ratio of 0.958 determined from the E.ON database. The standard deviation of the S factors in the database, using the NCV calculated from composition, is about 0.7% (relative). The standard uncertainty for the determination of NCV for a single sample is also 0.7% giving a combined uncertainty at 95% confidence of about 2% (relative) assuming a coverage factor of 2. This has been used in the overall uncertainty estimate when using a fixed fuel factor for hard coal. This uncertainty is also applicable to relatively dry processed biomass, with a moisture content below 25% by mass, that is typically co-fired with coal.

The expanded uncertainty associated with the use of the EN 12952-15 heating value correlation for a given coal sample, rather than using a fixed fuel factor value, is of the order of 1.1% based on this dataset, noting that either the measured or calculated CV can be used.

7 DETERMINATION BY CONTINUOUS MEASUREMENTS

Vattenfall has analysed parallel measurement data from the Swedish-EPA. Under the NO_x-fee system it is a legal requirement that parallel measurements are performed. In this work data from 765 parallel measurements using many different instrumental and calculation combinations were included.

In Sweden all plants with an annual output of more than 25 GWh are included in the Swedish NO_x-fee system. Most of these combustion plants use a stoichiometric calculation method to determine the flue gas flow from their stacks. The experience with this method is extremely good and it is also accepted by the Swedish Environmental Protection Agency, SEPA. SEPA also accepts it as a reference method that can be used during the required annual parallel flue gas flow measurements performed by a certified independent laboratory and compared with the monitoring equipment or calculation used by the plant.

Between 2005 and 2007, about 1000 comparisons of flue gas flow measurements were performed by independent emission monitoring laboratories by means of parallel measurements. In each of these parallel measurements campaigns, at least 10 measurement pairs are included. Amongst the circa 1000 parallel measurements reported to SEPA, the required information for a meaningful comparison was missing in about 250 cases. The remaining 765 data pairs have been divided into separate combinations depending on the measurement methods used. All data that has been used in this chapter has been received from SEPA.

In each report submitted to SEPA, the following information is given:

- Reference method (RM) used by the test laboratory
- Monitoring method (AMS)
- The systematic difference between the AMS and the RM
- The standard deviation between the AMS and the RM.

It is important to have in mind that all methods except the calculation method measure the total wet flue gas flow. The calculation method determines the dry flue gas flow so the measured moisture content must be available for comparison purposes.

Table 7.1 gives a breakdown of the combinations of AMS and the RM in the period 2005 to 2007.

Table 7.1 Methods included in the parallel measurements

Automated measurement method (AMS)	Reference method (RM)	Number of parallel measurements in each AMS-RM combination
Calculation in accordance to EN 12952-15	Calculation in accordance to EN 12952-15	328
Calculation in accordance to EN 12952-15	Pitot probe	324
Fan calibrated by tracer	Calculation in accordance to EN 12952-15	1
Fan calibrated by tracer	Pitot probe	28
Hot wire anemometer	Pitot probe	13
Pitot probe	Pitot probe	11
Ultrasonic	Calculation in accordance to EN 12952-15	3
Ultrasonic	Tracer injection	7
Ultrasonic	Pitot probe	46
Venturi	Pitot probe	4
TOTAL number of parallel measurements	-	765

The results for each category that contains more than 10 comparisons are shown in Table 7.2.

Table 7.2 Comparison of statistics between all methods; (AMS-RM) / AMS

AMS: RM	Unit	Calc. Calc.	Calc. Pitot	TE Pitot	Hot wire Pitot	Pitot Pitot	Ultrasonic Pitot
Number of parallel measurements	-	328	324	28	13	11	46
Mean value systematic difference	%	0.1	-3.3	-2.1	1.5	-6.7	-1.5
Mean value systematic difference (absolute terms)	%	3.1	7.9	7.2	5.0	7.3	7.8
Median value systematic difference	%	0.2	-2.7	-0.4	1.8	-5.5	-1.6
Median value systematic difference (absolute terms)	%	1.9	5.7	5.2	4.9	5.5	4.2
Mean value of standard deviation	%	0.9	3.0	4.2	1.8	1.4	1.7
Median value of standard deviation	%	0.5	2.2	2.9	1.5	1.0	1.2

AMS Method of flue gas determination at plant

RM Method used by certified measurement laboratory

Calc. Calculation from fuel and operational data

Pitot Pitot probe

TE Trace elements (calibration of the flue gas fan using a tracer)

Hot wire Hot wire anemometer

Ultrasonic Ultrasonic

Both the average systematic difference and the average standard deviation between the parallel measurements are of course lowest if both the AMS and the RM are based on the calculation method.

A reason for the slightly higher standard deviation if the AMS uses calculation and the RM uses Pitot probe is that the moisture content in the flue gas must be used to correct one set of results. Another reason is that the as received fuel analysis is based on an annual elementary analysis compensated for the annual average fuel water content. It is within the NOx fee system legislated that all plants, once a year, must send at least one fuel sample for analysis and use the results for the flue gas calculation in the forthcoming year. Most plants in Sweden use solid bio-fuel and the water content in bio-fuel can vary from one bulk car delivery to another. Many consultants have not analysed the moisture content during the parallel measurement.

In many cases (it is a routine at many plants) the water content in a sample from each arriving bulk car is determined. As their data-connecting unit registers all hourly flue gas flow they later can compensate to a more accurate water determination. This problem can easily be avoided by fuel sampling during the parallel measurement campaign and using that moisture content for the calculation of the flue gas flow. As mentioned elsewhere in this report it is the water content in the fuel that affects the calculation method of the flue gas flow.

Important results are:

The calibration method is the only method that determines the dry flue gas flow. This can be an advantage when combining the flue gas flow rate with a pollutant concentration reported on a dry basis and this also avoids the uncertainty related to the stack moisture measurement if the raw pollutant concentration is measured on a dry basis.

If both AMS and RM use calculation of the flue gas flow from the fuel composition both the standard deviation and the systematic difference is obviously very low compared to the other method combinations. The highest systematic difference between AMS and RM is in the group: Pitot probe – Pitot probe. The mean value of the systematic difference in this group is about twice as high as the other groups. The highest value of standard deviation is in the group: Calibration of flue gas fan – Pitot probe.

There is a relatively high standard deviation in the group: Calculation – Pitot probe. Two reasons for this have been identified. First of all, and most importantly, the standard deviation of the measurement of the stack moisture content is included. Also, in some cases, the moisture content in the fuel has not been measured during the parallel measurement. If the fuel moisture content is variable, it is important to sample the fuel at each measurement point.

The most important conclusion is, of course, that the calculation of flue gas flow is at least as good as any other method if both the standard deviation and the systematic differences are taken into account. However, for fuels with variable moisture content, it is very important to take this into account in the flue gas flow calculation; and the fuel moisture should be measured for each data pair taken during the parallel measurement campaign.

However, it should also be noted that the quality of the manual reference method measurements should also improve once there is a recognised CEN standard reference method available.

8 SUMMARY

Basic fuel factors

The volume of flue gas generated by the combustion of a known quantity of fuel is required. On a thermal input basis, the fuel factor does not vary substantially for a given fuel type and a fixed value is often sufficient. The volume of dry, stoichiometric flue gas per MJ of net supplied energy, S , is given in Table 8.1 for a range of fuels. An estimate of the uncertainty of the fuel constant is also given in the Table based on a comparison of the correlated values with an exact mass balance approach for a range of samples. The fuel factors have been derived in accordance with EN 12952-15 (Water-tube boilers and auxiliary installations – Part 15: Acceptance tests).

The gas fuel factor is appropriate for Group H natural gas (EN 437:2003) provided that this is also natural gas as defined in Directive 2010/75/EU on industrial emissions (integrated pollution prevention and control) in which the methane content is higher than 80%.

Table 8.1 Fossil fuel factors

Fuel Factor	Fuel type		
	Gas	Liquid	Solid
S <i>m^3/MJ at 0% O_2 dry 273.15K & 101.325kPa</i>	0.240	0.244	0.256
$U_{R,95\%}$	$\pm 0.7\%$	$\pm 1.5\%$	$\pm 2.0\%$

Note: Relative uncertainty (U_R) is quoted at 95% confidence assuming a normal data distribution and a coverage factor of 1.96 unless otherwise stated.

The liquid fuel factor is appropriate for light fuel oils noting that a factor of $0.248 m^3/MJ$ is appropriate for Heavy Fuel Oil.

The solid fuel factor is appropriate for commercially traded hard coal and processed biomass with a moisture content less than 25% by mass. At the reference oxygen concentration for solid fuels (6 vol%), this equates to a Fuel Factor of 0.359 m³/MJ or 359 m³/GJ. A lower uncertainty can generally be achieved for these fuels by applying a correction for the net calorific value (NCV).

Factors corrected for calorific value

A wider range of fuels can be considered, and a lower uncertainty can be achieved, by applying a correction for the net calorific value (NCV) of the as received fuel.

The NCV correction is derived from Annex A of EN 12952-15:

$$S = a / H_{(N)} + b$$

where $H_{(N)}$ is the Net Calorific Value of the as received fuel in MJ/kg.

Table 8.2 NCV correction factors

Parameter	Fuel type		
	Gas	Liquid	Solid
a	0.64972	1.76435	-0.06018 γ_F
b	0.22553	0.20060	0.25437 (1 + 2.4425 $\gamma_{H_2O} / H_{(N)}$)

For gaseous fuels, it may be more convenient to employ the volumetric NCV (MJ/m³ at 0°C) to obtain the volumetric flow factor (m³/m³) in which case $a = 0.199$ and $b = 0.234$. These verified factors are taken from the current approach in the Netherlands.

For liquid fuels, it is recommended that this correlation is used for light fuel oils only and other liquid fuel types should be evaluated from the fuel composition directly.

For solid fuels, the mass fractions of ash (γ_{Ash}) and moisture (γ_{H_2O}) in the as received fuel need to be taken into account in Table 8.2 using the dry, ash free, fuel mass fraction (γ_F), where:

$$\gamma_F = 1 - \gamma_{Ash} - \gamma_{H_2O}$$

If the net calorific value of the fuel stream is variable, the uncertainty associated with the fuel variability must be estimated from multiple fuel samples.

Factors derived from fuel composition

For solid fuels, EN 12952-15 (§8.3.4.2) also defines a method for determining the mass specific fuel factor, V_{God} (m^3/kg), from the as received fuel composition based on an ultimate analysis:

$$V_{\text{God}} = 8.8930 \gamma_{\text{C}} + 20.9724 \gamma_{\text{H}} + 3.3190 \gamma_{\text{S}} - 2.6424 \gamma_{\text{O}} + 0.7997 \gamma_{\text{N}}$$

where γ is the mass fraction of an individual fuel component in the supplied fuel (as received) and C, H, S, O and N are the elements carbon, hydrogen, nitrogen, oxygen and sulphur.

This is then divided by $H_{(\text{N})}$ to obtain the energy specific fuel factor S:

$$S = V_{\text{God}} / H_{(\text{N})}$$

For inhomogeneous solid fuels, for which it is difficult to obtain representative samples, it is recommended that the measured calorific value is checked using a calculated value of $H_{(\text{N})}$ (MJ/kg) using the following formulas.

$$H_{(\text{N})} = H_{(\text{G})} - 21.22 \gamma_{\text{H}} - 0.08 (\gamma_{\text{O}} + \gamma_{\text{N}}) - 2.4425 \gamma_{\text{H}_2\text{O}}$$

The above equation is from ISO 1928 (Solid mineral fuels - Determination of gross calorific value by the bomb calorimetric method and calculation of net calorific value) and requires $H_{(\text{G})}$, the Gross Calorific Value, either measured or calculated as follows.

$$H_{(\text{G})} = 34.1 \gamma_{\text{C}} + 132.2 \gamma_{\text{H}} + 6.86 \gamma_{\text{S}} - 12 \gamma_{\text{O}} - 12 \gamma_{\text{N}} - 1.53 \gamma_{\text{Ash}}$$

This equation is taken from the Coal Conversion Systems Technical Data Book (US DOE Report DOE/FE/05157-5, 1984). Note that methods for obtaining the fuel composition on an 'as received' basis are described in ISO 1170 (Coal and coke – Calculation of analyses to different bases). The agreement between measured and calculated CV should be within 5%.

If the composition of the fuel stream is variable, the uncertainty associated with the fuel variability must be estimated from multiple fuel samples. For example if the fuel moisture content is varied it is important to sample fuel during a measurement campaign for later analysis of the moisture content.

Performance requirements

Based on the uncertainty analyses presented earlier, the target overall performance requirement for the dry flue gas flow rate calculation is given by fuel type in Table 8.3 for which the method of determination is calculation from fuel factor and energy consumption.

The corresponding performance requirements for the main calculation inputs are given in Table 8.4.

Table 8.3 Performance requirements of the calculation approach

Fuel	Criterion
Gas	$\leq 2.0 \%$
Liquid	$\leq 3.0 \%$
Solid	$\leq 7.5 \%$

Table 8.4 Performance requirements of main input parameters

Parameter	Criterion	Method of determination
Energy input - from fuel consumption		
Fuel flow rate	$\leq 1.5\%$ of value	Mass or volume flow meter with traceable calibration certificate.
Net Calorific Value	$\leq 0.5\%$ of value	Determination or instrument calibration by a laboratory accredited to ISO 17025.
Energy input - from energy production		
Electrical power	$\leq 0.5\%$ of value	Electricity meter.
Net thermal efficiency	$\leq 5.0\%$ of value	Heat balance verified by performance testing and/or annual fuel consumption and energy production.
Fuel factor		
Gas	$\leq 0.7\%$ of value	Determination from fuel composition, NCV or a defined constant fuel factor.
Liquid	$\leq 1.5\%$ of value	
Solid	$\leq 2.0\%$ of value	

9 REFERENCES

CEN 2003; EN 12952-15 Water-tube boilers and auxiliary installations – Part 15: Acceptance tests

DIN 1979; DIN 1942 Abnahmeversuche an Dampferzeugern (VDI – Dampferzeugerregeln); Juni 1979

DIN 1994; DIN 1942 Acceptance test code for steam generators (VDI-rules for steam generators); February 1994

EN 437,2003; Test gases - Test pressures - Appliance categories

E.ON, 2008; Deliver energy to the world

EU, 2010; DIRECTIVE 2010/75/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 24 November 2010 on industrial emissions

VGB / EURELECTRIC, 2008; European Wide Sector Specific Calculation Method for Reporting to the European Pollutant Release and Transfer Register

Balancing and Settlement Code, Code of practice for the calibration, testing and commissioning requirements of metering equipment for settlement purposes, Code of Practice No 4

APPENDIX I EXTENDING THE INPUT BASED APPROACH TO BIOMASS AND WASTE

In the previous chapters it is already shown that the moisture content of the fuel impacts on the fuel factor. With increasing moisture content the fuel factor increases, principally because of the negative heating value of the water fraction. In the following elaboration the interrelation is shown:

The validation of the EN12952-15 standard methods resulted in an acceptable general fuel factor to calculate dry flue gas. However a fixed factor only applies for the net caloric value based on dry matter. On as received basis the water content is part of the stoichiometric composition. Figure 1 presents a method to calculate the fuel factor and thus the stoichiometric flue gas volume for dry or wet fuel according to empirical method of the EN 12952-15 standard.

When the dry fuel net caloric value $H(N)_d$ is known, the dry stoichiometric flue gas volume (V_{God}) in m^3/kg can be calculated as followed: In Figure 1, the fuel moisture content line of 0% is followed to pin point the desired $H(N)_d$ (red number). Once this point is found, the fuel factor can be read from the y-axis following the horizontal dotted line. The V_{God} can be calculated according formula 1. Hereby, the fuel factor (S) of 0.252 is validated as general fuel factor for calculating V_{God} for a dry solid fuel.

$$V_{God} = S \cdot H(N)_d \quad [1]$$

To determine the caloric value as received ($H(N)_{ar}$) and flue gas volume as received (V_{Gar}) the fuel moisture content is required. The red line ($H(N)_{ar}$) has to be followed until it crosses the determined fuel moisture content on the black line. Once this point is determined, reading the x-axis following the vertical dotted line gives the $H(N)_{ar}$ and reading the y-axis following the horizontal vertical line gives the fuel factor to calculate V_{Gar} according to formula 2.

$$V_{Gar} = S \cdot H(N)_{ar} \quad [2]$$

When the caloric value as received is known the procedure mentioned above have to be reversed.

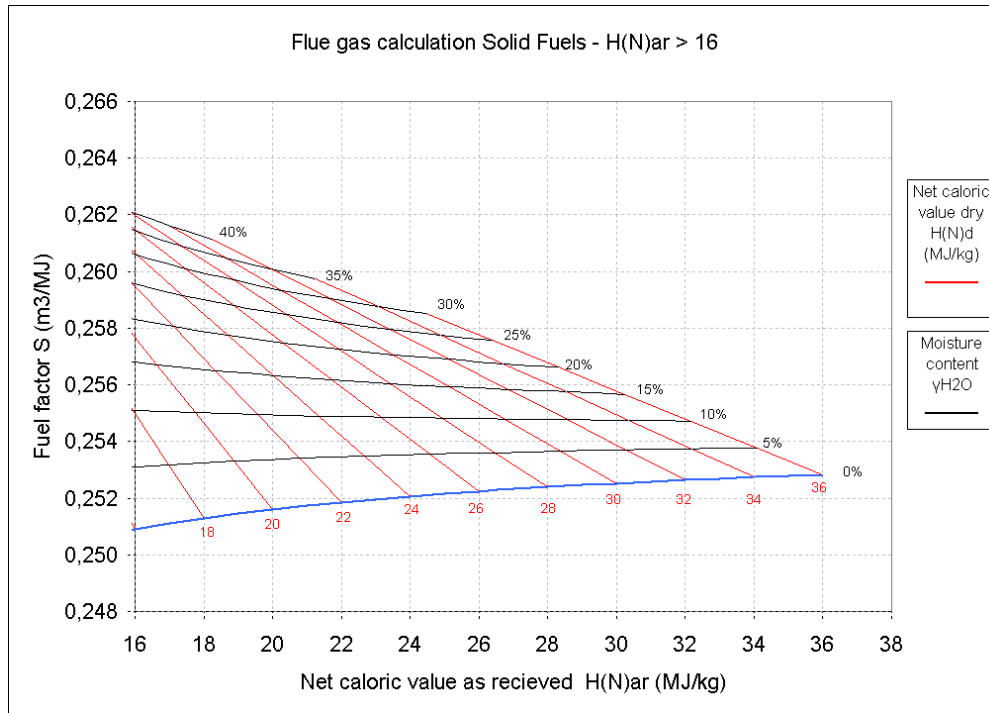


Figure 1 Dependence of the fuel factor on heating value and moisture content

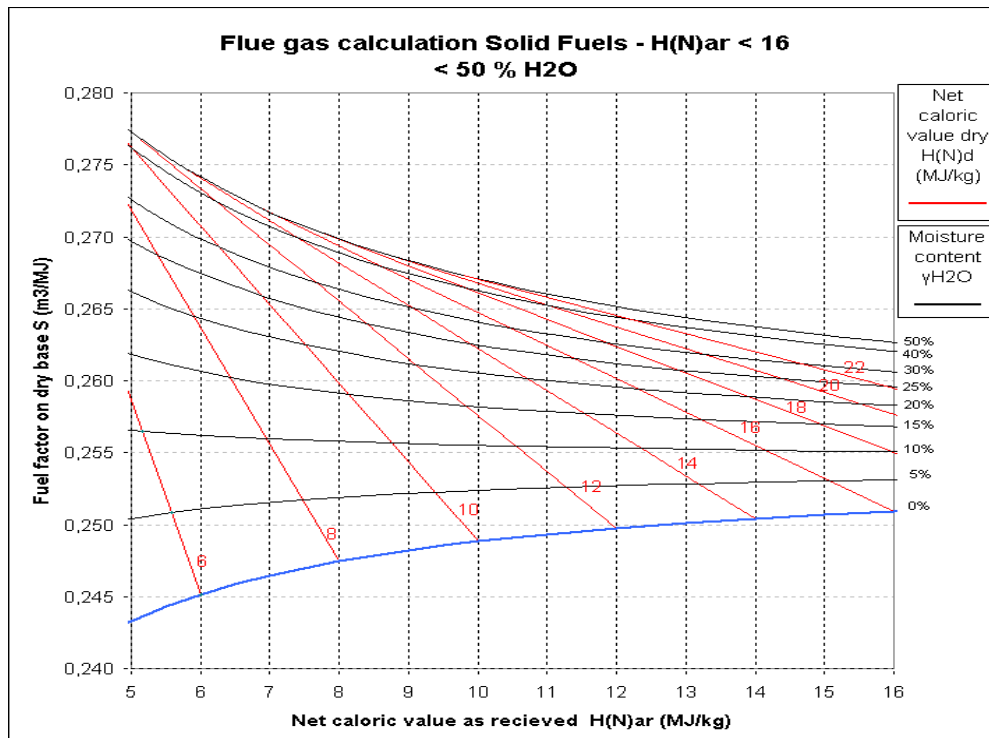


Figure 2 Dependence of the fuel factor from heating value and high moisture content

Example 1: Flue gas calculation based on $H(N)_d$.

A coal sample is used for the example where $H(N)_d$ has a value of 27.5 MJ/kg. In order to calculate the V_{God} the S has to be determined according to Figure 1. The bold blue line indicates $H(N)_d$ because the fuel moisture content is 0% (Point 1). Point 2 indicates the right fuel factor for calculating the V_{God} .

$$V_{God} = S \cdot H(N)_d = 0.2524 \cdot 27.5 = 6.94 \text{ m}^3/\text{kg}$$

To determine the $H(N)_{ar}$ the red line has to be followed to the desired fuel moisture content. For this example, a moisture content of 10% is used which results in point 1 to point 3. From point 3, the $H(N)_{ar}$ (point 3 to point 5 vertical) and the S (point 3 to point 4 horizontal) can be determined for calculating the V_{Gar} .

$$V_{Gar} = S \cdot H(N)_{ar} = 0.2548 \cdot 24.3 = 6.19 \text{ m}^3/\text{kg}$$

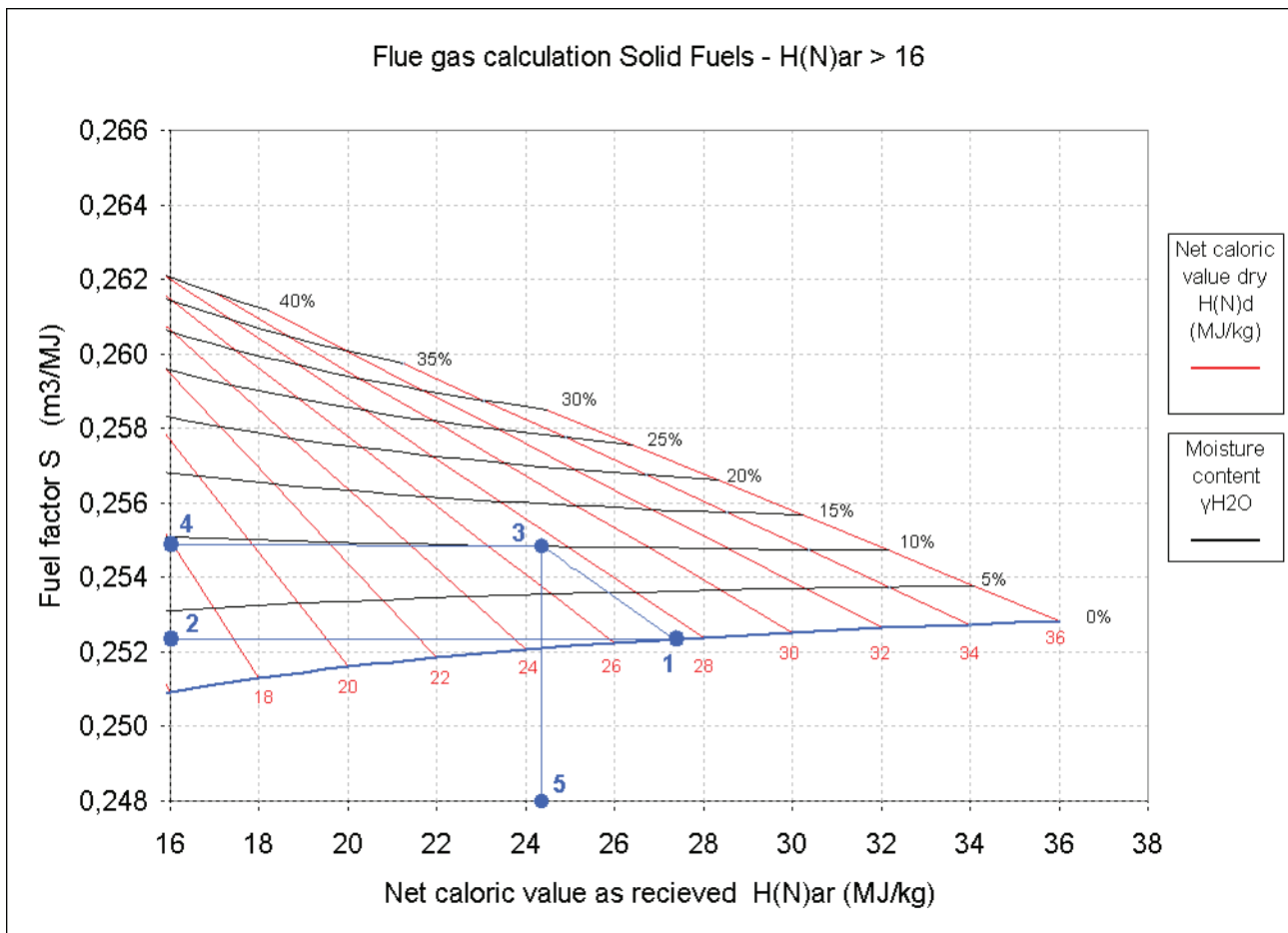


Figure 3 Example 1; the fuel factor calculated for wet and dry fuel

Example 2: Flue gas calculation based on $H(N)_{ar}$.

A biomass sample is used for example where the $H(N)_{ar}$ has a value of 8,0 MJ/kg and a moisture content of 30%. Because low and high caloric values can not be presented clear in one graph, Figure 4 is used to illustrate the calculation for example 2. Point 1 indicates the $H(N)_{ar}$ with a moisture content of 30%. Point 2 indicates the right fuel factor for calculating the V_{God} .

$$V_{Gar} = 0.266 \cdot 8.0 = 2.13 \text{ m}^3/\text{kg}$$

To determine the $H(N)_d$ the red line has to be followed to a moisture content of 0% which results in point 1 to point 3 ($H(N)_d = H(N)_{ar}$ if moisture content is 0%). From point 3, the S (point 3 to point 4 horizontal) for calculation of V_{God} .

$$V_{God} = 0.250 \cdot 12.4 = 3.10 \text{ m}^3/\text{kg}$$

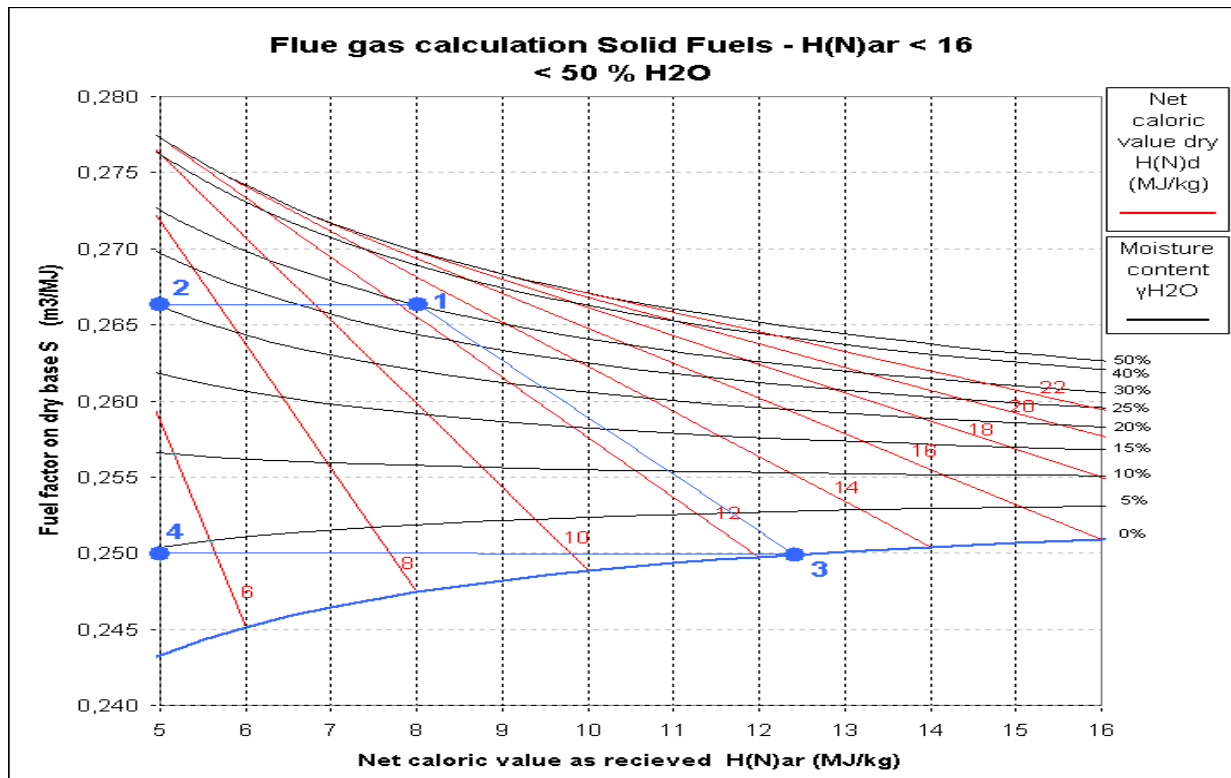


Figure 4 Example 2; the fuel factor calculated for a wet and dry biomass fuel

APPENDIX II OVERVIEW OF TC STANDARDS

Standardization of solid fuels within CEN.

The Technical Committee CEN/TC 335 works with “Solid Bio Fuels”, SIS holds the secretariat of CEN/TC 335.

Within CEN/TC 335 the following standards and technical reports had been written. Many of them are irrelevant for flue gas calculations.

Solid bio fuels

Document number	Title	Document type	Relevance for the flue gas calculation procedure
CEN/TC 14588:2003	Terminology, definitions and descriptions	TS	Some relevance
EN 14774-1: 2009	Part 1: Total moisture – reference method	Standard	Very important
EN 14774-2: 2009	Part 2: Total moisture – Simplified method	Standard	Very important
EN 14774-3: 2009	Part 3: Moisture in general analysis sample	Standard	Very important
EN 14775: 2009	Determination of ash content	Standard	Very important
CEN/TS 14778-1: 2006	Part 1: Methods of sampling	TS	Important
CEN/TS 14778-2: 2006	Part 2: Methods for sampling particulate material transported in lorries	TS	Important
CEN/TS 14449: 2006	Sampling – Methods for preparing sampling plans and sampling certificates	TS	Some relevance
CEN/TS 14780: 2006	Methods for sample preparation	TS	Important
EN 14918:2010	Determination of calorific value	Standard	Very important
CEN/TS 14961: 2005	Fuel specifications and classes	TS	Some relevance
EN 14961-1: 2010	Fuel specifications and classes. Part 1: General requirements	Standard	Some relevance
EN 15103:2010	Determination of bulk density	Standard	Irrelevant

CEN/TS 15104: 2006	Determination of total content of carbon, hydrogen and nitrogen – Instrumental method	TS	Very important
CEN/TS 15105: 2006	Methods of determination of the water soluble content of chloride, sodium and potassium	TS	Irrelevant
EN 15148:2009	Determination of the content of volatile matter	Standard	Irrelevant
CEN/TS 15149-1: 2006	Methods of the determination of particle size distribution (oscillating screen)	TS	Irrelevant
CEN/TS 15149-2: 2006	Methods of the determination of particle size distribution (vibrating screen)	TS	Irrelevant
CEN/TS 15149-3: 2006	Methods of the determination of particle size distribution (rotary screen)	TS	Irrelevant
CEN/TS 15150: 2006	Methods for the determination of particle density	TS	Irrelevant
EN 15210-1: 2010	Determination of mechanical durability of pellets and briquettes. Part 1 Pellets.	Standard	Irrelevant
EN 15210-2: 2006	Methods for the determination of mechanical durability of pellets and briquettes. Part 2 Briquettes.	TS	Irrelevant
CEN/TS 15234: 2006	Fuel quality assurance	TS	Important
CEN/TS 15289: 2006	Determination of total content of sulphur and chlorine	TS	Important
CEN/TS 15290: 2006	Determination of major elements	TS	Irrelevant
CEN/TS 15295: 2006	Calculation of analyses to different bases	TS	Very important
CEN/TS 15297: 2006	Determination of minor elements	TS	Irrelevant
CEN/TS 15370-1: 2007	Methods for the determination of ash melting behavior. Part 1: Characteristic temperature method	TS	Irrelevant

The Technical Committee CEN/TC 343 works with “Solid Recovered Fuels”, SFS holds the secretariat of CEN/TC 343.

Within CEN/TC 343 the following standards and technical reports had been written. Many of them are irrelevant for flue gas calculations.

Solid recovered fuels

Document number	Title	Document type	Relevance for the flue gas calculation procedure
CEN/TR 14980:2006	Relative difference between biodegradable and biogenic fraction of SRF	TR	Irrelevant
CEN/TS 15357: 2006	Terminology, definitions and descriptions	TS	Important
CEN/TS 15358: 2007	Quality management systems – Particular requirements for their application to the production of solid recovered fuel	TS	Some relevance
CEN/TS 15359: 2006	Specifications and classes	TS	Very important
CEN/TS 15400: 2006	Methods for the determination of calorific value	TS	Very important
CEN/TS 15401: 2007	Methods for the determination of bulk density	TS	Irrelevant
CEN/TS 15402: 2007	Part 2: Methods for the determination of the content of volatile matter	TS	Irrelevant
CEN/TS 15403: 2007	Methods for the determination of ash content	TS	Very important
CEN/TS 15404: 2007	Methods for the determination of ash melting behaviour by using characteristic temperatures	TS	Irrelevant
CEN/TS 15405: 2007	Methods for the determination of density of pellets and briquettes	TS	Irrelevant
CEN/TS 15406: 2008	Methods for the determination of bridging properties of bulk material	TS	Irrelevant
CEN/TS 15407:	Method for the determination of carbon	TS	Very important

2007	(C), hydrogen (H) and nitrogen (N) content		
CEN/TS 15408: 2007	Methods for the determination of sulphur (S), chlorine (Cl), fluorine (F) and bromine (Br) content	TS	Very important
CEN/TS 15410: 2007	Method for the determination of the content of major elements (Al, Ca, Fe, K, Mg, Na, P, Si, Ti)	TS	Irrelevant
CEN/TS 15411: 2007	Method for the determination of the content of trace elements (As, Ba, Be, Cd, Co, Cr, Cu, Hg, Mo, Mn, Ni, Pb, Sb, Se, Ti, V and Zn)	TS	Irrelevant
CEN/TS 15412: 2008	Methods for the determination of metallic aluminum	TS	Irrelevant
CEN/TS 15413: 2008	Method for the preparation of the test sample from the laboratory sample	TS	Important
CEN/TS 15414-1: 2008	Determination of moisture content using oven dry method. Part 1: Determination of total moisture by a reference method	TS	Very important
CEN/TS 15414-2: 2008	Determination of moisture content using oven dry method. Part 2: Determination of total moisture by a simplified method	TS	Very important
CEN/TS 15414-3: 2008	Determination of moisture content using oven dry method. Part 3: Moisture in general analysis sample	TS	Very important
CEN/TS 15415: 2008	Determination of particle size distribution by screen method	TS	Irrelevant
CEN/TS 15440: 2007	Method for the determination of biomass content	TS	Irrelevant
CEN/TS 15442: 2008	Methods for sampling	TS	Important
CEN/TS 15443: 2008	Methods for laboratory sample preparation	TS	Important
CEN/TS 15747: 2008	¹⁴ C-based methods for the determination of the biomass content	TS	Irrelevant

UNCERTAINTIES MENTIONED IN THE RELEVANT DOCUMENTS FOR BIO FUELS

EN 14774-1-3: 2009 - Total moisture Part 1-3.

Part 1 and 2: reference method and simplified method

Because of the varying nature of the solid bio fuels no precision statement (repeatability and reproducibility) for the method is listed.

Part 3: general analysis sample

Repeatability must be $< 0,2 \%$

Reproducibility: because of the varying nature of the solid bio fuels no precision statement reproducibility for the method is listed.

EN 14775:2009 - Determination of ash content.

Ash content (%)	Maximum acceptable differences between results	
	Same laboratory (repeatability)	Different laboratories (reproducibility)
Less than 10 %	0,2 % absolute	0,3 % absolute
Equal to or greater than 10 %	2,0 % of the mean results	3,0 % of the mean results

EN 14918:2010 – Determination of calorific value.

Repeatability limit:

The results of duplicate determinations, carried out in the same laboratory by the same operator with the same apparatus within a short interval of time on the same analysis sample, shall not differ by more than 120 J/g.

Reproducibility limit:

The means of the results of duplicate determinations carried out in each of two laboratories, on representative portions taken from the same sample at the last stage of sample preparation, should not differ by more than 300 J/g.

CEN/TS 15104:2005 – Determination of total content of carbon, hydrogen and nitrogen – instrumental methods.

	Maximum acceptable differences between results (on dry basis)	
	(repeatability)	(reproducibility)
Carbon content	0,5 % absolute	1,5 % absolute
Hydrogen content	0,25 % absolute	0,5 % absolute
Nitrogen content	10 % relative if N > 0,5 % 0,05 % absolute if N < 0,5 %	20 % relative if N > 0,5 % 0,1 % absolute if N < 0,5 %

CEN/TS 15289:2006 – Determination of total content of sulphur and chlorine.

Content of sulphur and chlorine (dry basis)	Maximum acceptable differences between results	
	Same laboratory (repeatability)	Different laboratories (reproducibility)
Chlorine ≤ 500 mg/kg	50 mg/kg	100 mg/kg
Chlorine > 500 mg/kg	10 % of mean results	20 % of mean results
Sulphur ≤ 500 mg/kg	50 mg/kg	100 mg/kg
Sulphur > 500 mg/kg	10 % of mean results	20 % of mean results

CEN/TS 14778-1:2005 – Sampling – Part 1 – Methods of sampling.

Information on the precision of sampling will be added when results from practice are available.

CEN/TS 14778-2:2008 – Sampling - Part 2: Methods for sampling particulate material transported by lorries.

There are no chapter concerning precision included in the actual TS.

CEN/TS 14780:2006 – Methods for sample preparation.

There are no chapter concerning precision included in the actual TS.

CEN/TS 15234:2006 – Fuel quality assurance.

There are no chapter concerning precision included in the actual TS.

Uncertainties mentioned in the relevant documents for recovered fuels

CEN/TS 15400:2006– Determination of calorific value.

Repeatability limit:

The results of duplicate determinations, carried out in the same laboratory by the same operator with the same apparatus within a short interval of time on the same analysis sample, shall not differ by more than 200 J/g.

Reproducibility limit:

The means of the results of duplicate determinations carried out in each of two laboratories, on representative portions taken from the same sample at the last stage of sample preparation, should not differ by more than 400 J/g.

CEN/TS 15403:2007 – Methods for the determination of ash content.

Because of the varying nature of the solid recovered fuels covered by this TS, at the present time it is not possible to give a precision statement (repeatability or reproducibility) for this test method.

CEN/TS 15407:2006 – Methods for sample the determination of carbon (C), hydrogen (H) and nitrogen (N) content.

There are no chapter concerning precision included in the actual TS.

CEN/TS 15408:2006 – Methods for sample the determination of sulphur (S), chlorine (Cl), fluorine (F) and bromine (Br) content.

There are no chapter concerning precision included in the actual TS.

CEN/TS 15414-1-3: 2008 - Total moisture Part 1-3.

Part 1 and 2: reference method and simplified method

Because of the varying nature of the solid recovered fuels covered by this TS, at the present time it is not possible to give a precision statement (repeatability or reproducibility) for this test method.

Part 3: general analysis sample

Repeatability must be $< 0,2 \%$ (carried out in the same laboratory, by the same operator, with the same apparatus on representative portions weighed out at the same time from the analysis sample).

Because of the varying nature of the solid recovered fuels covered by this TS, at the present time it is not possible to give a precision statement (repeatability or reproducibility) for this test method.

CEN/TS 15413: 2008 - Method for the preparation of the test sample from the laboratory sample.

There are no chapter concerning precision included in the actual TS.

CEN/TS 15442: 2008 - Methods for sampling.

In order to mention reliable and representative data on the precision of the sampling methods a validation investigation shall be performed. This data is not yet available.

CEN/TS 15443: 2008 - Methods for laboratory sample preparation.

There is no chapter concerning precision included in the actual TS.