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Determination of the Efficiencies of Automatic Biomass Combustion Plants

Evaluation of Different Methods for Efficiency Determination and Comparison of Efficiency and Emissions for Different Operation Modes

Final report on behalf of

International Energy Agency, IEA Bioenergy Task 32

prepared by

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Zürich and Gembloux, 22. November 2006

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1. Abstract

The main objective of the present investigation is the evaluation and comparison of different methods for the determination of the efficiencies of automatic biomass combustion plants. For this purpose, detailed formula for the combustion efficiency, the boiler efficiency and the annual plant efficiency are described and methods for direct and indirect determination are distinguished. Furthermore, a calculation of the uncertainties is carried out for each method.

The second objective of the study is a comparison of efficiencies and emissions at different operation modes, i.e. at full load and at part load operation.

The third objective of the present investigation is the introduction and validation of a modified formula for indirect determination of the annual plant efficiency. The determination of the annual plant efficiency together with a measurement of the annual heat production is well suited as cost-effective method for the fuel accounting for plants with one single fuel supplier.

To evaluate the influence of the plant operation on the efficiency, measurements were performed on a 550 kW grate boiler on a test bench in Belgium. Combustion efficiency, boiler efficiency and emissions have been determined at stationary operation at 100%, 60%, 30% and 10% of the nominal load. The combustion efficiency calculated by indirect determination method resulted for 100% down to 30% load in a range of 90.9 ±0.7% to 87.8 ±0.7%, the boiler efficiency calculated by indirect determination resulted in a range of 86.2 ±1.7% to 84.2 ±4.8%. For the combustion efficiency, high accuracy is achieved, while the uncertainty of the boiler efficiency is quite small for 100% load, but increases significantly with decreasing load, which is mainly due to the uncertainty of the thermal losses by radiation, convection and ash losses. The boiler efficiency calculated by direct determination method resulted for 100% down to 30% load in a range of 78.6 ±9.5% to 80.7 ±10.5%. The high uncertainty is mainly a result of the uncertainty of the fuel mass flow at the test bench.

To evaluate the determination of the annual plant efficiency, measurements were performed on a 350 kW understoker boiler operating in practice in Switzerland. For this application, the annual plant efficiency was investigated by the direct and the indirect determination method. The annual plant efficiency by direct determination method (reference) resulted in 78.4 ±10.1%. The high uncertainty of the weight-based measurement is due to the uncertainty of the net calorific value and the variations of the water content of the fuel used in the plant in practical operation. The annual plant efficiency calculated by the indirect determination method, i.e. the formula proposed for fuel accounting, was 80.6 ±5.6% and hence more accurate. Since the expanded uncertainty of the reference method was higher, the indirect determination method could not be experimentally validated.

Keywords: Efficiency determination, combustion efficiency, boiler efficiency, annual plant efficiency.

2. Summary

Fuel accounting in large biomass plants is usually based on the fuel mass and the water content of the fuel delivered to the plant. In small and medium plants, the determination of the fuel mass is usually not possible due to cost reasons. Consequently, the fuel accounting is often based on the fuel volume, which can easily be determined. However, the transformation from the fuel volume to the energy content is related to significant uncertainties, since the bulk density of wood chips and other biomass fuels can vary in a wide range. As an alternative, the fuel accounting can be performed based on the annual heat production of the combustion plant. This model is most commonly applied in Switzerland, where one single regional fuel supplier is respected for the fuel delivery. However, this method for fuel accounting demands for an estimation or determination of the annual plant efficiency. Hence a formula based on theoretical considerations was introduced in [1, 2], which is applied in many plants nowadays. Together with the measurement of the annual heat production, it enables a cheap accounting for the fuel in cases of one single fuel supplier.

The main objective of the present investigation is the evaluation and comparison of different methods for the determination of efficiencies of automatic biomass combustion plants with theoretical and experimental investigations. The following three efficiencies, i.e. combustion efficiency, boiler efficiency and annual plant efficiency of biomass combustion are described in detailed formula. The efficiencies can be determined by direct and indirect determination methods. A calculation of the uncertainties for each method is carried out. The uncertainties are based on the combined standard uncertainties u_c and the expanded uncertainty U with a coverage factor of k=2 implying a confidence interval or level of confidence of app. 95%. A second objective is the comparison of efficiency and emissions at different operation modes, i.e. full load and part load operation. A third objective of the present investigation is the introduction and validation of a modified formula for indirect determination of the annual plant efficiency.

On a 550 kW biomass grate boiler test bench in Belgium, combustion efficiency, boiler efficiency and emissions have been determined at stationary operation at 100%, 60%, 30% and 10% of the nominal load. The combustion efficiency calculated by the indirect determination method resulted for 100% to 30% load in a range of 90.9 ±0.7% to 87.8 ±0.7%, the expanded uncertainty being quite small. For 10% load, the combustion efficiency was 86.1 ±2.0%.
The boiler efficiency calculated by indirect determination method resulted for 100% to 30% in a range of 86.2 ±1.7% to 84.2 ±4.8%. For 10% of the nominal load, the boiler efficiency was 66.1 ±14.4%. The expanded uncertainty is still quite small for 100% load, but increases significantly with decreasing load due to the uncertainty of the thermal losses by radiation, convection and ash losses during stationary operation of the boiler.
The boiler efficiency calculated by the direct determination method resulted for 100% to 30% load in a range of 78.6 ±9.5% to 80.7 ±10.5%, the expanded uncertainty being quite high. For 10% of nominal load, the boiler efficiency was 62.8 ±15.8%. The high expanded uncertainty was mainly due to the uncertainty of the fuel mass flow at the test bench.
The investigated grate boiler enabled high efficiency and low emissions for the whole heat load range of 100% down to 30%, but achieved low efficiency and high emissions at 10%.

On a 350 kW biomass understoker boiler operating in practice in Switzerland, the annual plant efficiency was investigated by direct and indirect determination method. For the direct determination method, the annually consumed fuel was determined by weight (highly accurate) and by volume (as easier alternative but with high uncertainty), the annual heat production was measured by a heat meter. In addition, the fuel water content and the fuel type (hard wood or soft wood) were registered. For the indirect determination method, the formula proposed for fuel accounting was applied.
The annual plant efficiency calculated by direct determination method was 78.4 ±10.1% based on fuel weight and 81.7 ±12.5% based on fuel volume. The high uncertainty of the weight-based measurement is due to the uncertainty of the net calorific value and the variations of the water content of the fuel at the plant in practical operation. The uncertainty of the volume-based measurement is only slightly higher due to the well known fuel type and bulk density in the investigated case. In case of varying fuel type and without well-known net calorific value and bulk density, the uncertainty of the volume-based measurement is far higher than the weight-based measurement.
The annual plant efficiency calculated by the indirect determination method, i.e. the formula proposed for fuel accounting, was 80.6 ±5.6%. The expanded uncertainty of the reference method, i.e. the direct determination method for the annual plant efficiency calculated as heat output divided by energy input based on fuel mass, was less accurate (78.4 ±10.1%). Therefore, a validation of the indirect determination method, i.e. the formula proposed for fuel accounting, could not be be performed.

3. Introduction

3.1. Background

Definitions of efficiencies

The *combustion efficiency* is defined as energy input minus heat losses in the flue gas. It can easily be determined with a fast and reliable measurement of the flue gas composition and temperature. Additional information on the fuel is needed, while no further information on the plant is necessary. Hence the combustion efficiency is often used for an instantaneous comparison of different boilers and/or operation modes, since the influence of varying excess air ratio or flue gas temperature can immediately be evaluated.

The *boiler efficiency* is defined as useful heat output per time unit divided by energy input per time unit. It is of interest for the plant operator, as it considers also losses of the boiler by radiation and by unburned fuel in the ash. Although it is determined as instantaneous value, it must be considered that the boiler has a significant heat and fuel storage capacity. Hence reliable information about the boiler efficiency can only be found during stationary conditions or as integrated value over a certain operation period.

If the useful heat (produced heat) and the amount of burnt fuel are determined during a whole heating season, the *annual plant efficiency* can be determined dividing the annual useful heat by the annual energy input. In this case, additional losses caused by the systems integration of heat production and heat consumption as well as additional losses occurring during standby-mode of the boiler are also considered. The annual plant efficiency is of interest for the operator for economic reasons. However, it is not suited for a comparison of different boilers, as the system integration of the boiler into the combustion plant has a major impact on the annual plant efficiency.

The combustion efficiency and the boiler efficiency can be considered as instantaneous values. As a matter of principle, the annual plant efficiency is a time-integrated value.

Efficiency can be determined either by the use of a direct or an indirect determination method. In the direct determination method, the efficiency is defined as the ratio between heat output (water) and heat input (i.e., calorific value of the fuel) (kWh/kWh) or as the ratio between heat output load and heat input load (kW/kW). In the indirect determination method, the efficiency is defined as 100 percent minus thermal and chemical losses.

Influence of part-load operation

Automatic biomass combustion plants are operated in different modes. As they are often used in part load operation (specifically if in use as heating plants), the following operation modes are distinguished:

a) stationary full load operation (100%)

b) stationary part load operation (typically from 30…50% to 100%)

c) part load operation in standby mode with on/off operation of the fuel feeding to maintain a glow bed for re-ignition

d) on/off operation of the furnace with automatic ignition.

The type of part-load operation can significantly influence the annual plant efficiency. This is not considered by the combustion or the boiler efficiency. Since no data are available on the influence of the operation mode so far, it is of interest to collect experimental data on the influence of the part-load operation on the plant efficiency to enable development decisions for future applications.

Furthermore, the part-load operation mode can have a significant influence on the pollutant emissions. While start-up of the cold boiler in operation-mode d) can typically lead to high emissions, also glow bed support without heat demand in mode c) or part load operation in mode b) lead to high emissions if not conducted properly. Hence it is of interest to have information on the influence of the operation-mode on emissions during part-load operation to enable decisions for future applications.

Fuel accounting

The accounting of the fuel in large biomass plants is usually based on the fuel mass and the water content of the fuel delivered to the plant.

In small and medium plants, the determination of the fuel mass is usually not possible due to cost reasons and the fuel accounting is often based on the delivered fuel volume. The fuel volume can easily be determined. However, the transformation from the fuel volume to the energy content delivered to the plant is related to significant uncertainties, as the bulk density of wood chips and other biomass fuels can vary in a wide range.

As an alternative, the fuel accounting can be performed based on the heat production in the combustion plant. This model is most often applied e.g. in Switzerland, where one single regional fuel supplier is respected for the fuel delivery. However, this type of fuel accounting demands for an estimation of the annual plant efficiency. Hence a formula based on theoretical considerations was introduced in [1,2], which is applied in many plants nowadays. Together with the measurement of the annual heat production, it enables a cheap accounting for the fuel in cases of one single fuel supplier.

3.2. Aim of the Investigation

The main objective of the project is *the evaluation and comparison of different methods for the determination of efficiencies of automatic biomass combustion plants* with theoretical and experimental investigations.

For this purpose, the following three efficiencies, i.e. combustion efficiency, boiler efficiency and annual plant efficiency will be described by detailed formula. Since the efficiencies can be determined by different methods and since the three different types of efficiencies cannot be compared directly, a calculation of the uncertainties (error bars) for each method will be carried out.

For an assessment of the experimental determination of the three efficiencies, systematic measurements will be carried out on an automatic biomass combustion plant on a test bench in Belgium, which allows an independent operation for the measurements. Additional measurements will be carried out on one plant in practical operation in Switzerland.

During the experiments, a variation of the operation mode is planned that enables another objective, i.e. *a comparison of efficiency and emissions as a result of different types of part-load operation*. For this purpose, the mass flow of the flue gas will be measured or estimated by mass balance to enable the determination of total pollutant emissions for different operation modes.

An additional target of the present investigation is the *introduction and validation of a modified formula for indirect determination of the annual plant efficiency* by measurements. For this purpose, a model to estimate the annual plant efficiency is proposed and will be compared to the direct determination of the annual plant efficiency.

4. Determination of Efficiency

4.1. Direct and Indirect Determination Method

In the *direct determination method*, the efficiency is defined as the ratio between heat output (water) and heat input (fuel) (Eq. 4-1) or as the ratio between heat output load and heat input load (Eq. 4-2):

$$\eta_{direct} = \frac{Q_{Out}\,[kWh]}{Q_{In}\,[kWh]} \quad [-] \qquad \text{(Eq. 4-1)}$$

$$\eta_{direct} = \frac{\dot{Q}_{Out}\,[kW]}{\dot{Q}_{In}\,[kW]} \quad [-] \qquad \text{(Eq. 4-2)}$$

In the *indirect determination method*, the efficiency is defined as 1 minus losses plus gain through condensation of water vapour:

$$\eta_{indirect} = 1 - \frac{Heat\ Losses}{Heat\ in\ Fuel} + \frac{Heat\ Gain}{Heat\ in\ Fuel} \quad [-] \qquad \text{(Eq. 4-3)}$$

The heat losses consist of:

- thermal losses by sensible heat of dry flue gas and water vapour
- chemical losses by incomplete combustion
- thermal losses by radiation, convection and thermal conduction
- thermal losses in unburnt fuel (such as unburned carbon in ash residues)
- thermal gain from latent heat of condensed water vapour in flue gas (from water content in the fuel and from combustion of hydrogen)

The combustion efficiency is considered as an *instantaneous value*, whereas the boiler efficiency is considered as a quasi-instantaneous, *short-term value*, time-averaged over a period of hours only. As against, the annual plant efficiency per se is an *annual mean*. Table 4-1 shows an overview over the different methods for efficiency determination.

Table 4-1 Classification of methods for efficiency determination.

	Instantaneous Value	Short-term Value	Annual Mean
Methods for Efficiency Determination	**Combustion Efficiency** η_c	**Boiler Efficiency** η_b	**Annual Plant Efficiency*** η_{annual}
Direct Method		**o**	**o**
Indirect Method	**o**	**+**	**+**

o Standard determination method
+ Alternative determination method
* Plant: Boiler and systems integration of boiler; including both, boiler in operation mode and boiler in standby mode

4.2. Combustion Efficiency

4.2.1. Direct Determination Method for Combustion Efficiency

As the combustion efficiency is the momentary ratio between heat output (combustion) and heat input (fuel) or between heat output load (combustion) and heat input load (fuel), there is no direct determination method available.

4.2.2. Indirect Determination Method for Combustion Efficiency

Using the indirect determination method, the combustion efficiency is defined as 1 minus thermal losses by sensible heat of the flue gas minus chemical losses by incomplete combustion. According to DIN 4702, the determination of the thermal and chemical losses needs information about the specific volume of the dry flue gas and the water vapour in the flue gas as well as information about the specific heat capacity of the individual flue gas components.

For an easier technical application, a simplified formula with sufficient accuracy has been proposed [3,4]. Starting from the combustion reaction of biomass (for example wood), the heat within the individual flue gas components is determined and thus the thermal and chemical losses can be determined. The following simplifications of the exact formula lead to a simplified formula ((Eq. 4-4),(Eq. 4-5),(Eq. 4-6)), which results in an error < 0.2 % in comparison to the detailed formula:

- CO is neglected in the combustion reaction
- the excess air ratio is assumed as λ = 20.4 / (CO2 + CO)
- the specific heat capacities of the flue gas components are considered constant being the mean value in the temperature range of 0 – 200 °C

In the range CO < 0,5 Vol.-%, CO_2 > 5 Vol.-%, flue gas temperature < 400°C the **combustion efficiency** η_c of a biomass combustion plant is determined by the following equations:

$$\eta_c = 100 - L_{thermal} - L_{chemical} \quad [\%] \qquad \text{(Eq. 4-4)}$$

Where:				
	η_c	=	Combustion Efficiency	[%]
	$L_{thermal}$	=	Thermal losses by sensible heat of flue gas	[%]
	$L_{chemical}$	=	Chemical losses by incomplete combustion	[%]

$$L_{thermal} = \frac{(T_{Fg} - T_A)\left\{1,39 + \frac{122}{CO_2 + CO} + 0,02\ u\right\}}{\frac{NCV_{Dry\ Fuel}}{100} - 0,2442\ u} \quad [\%] \qquad \text{(Eq. 4-5)}$$

$$L_{chemical} = \frac{CO}{CO_2 + CO} \frac{11'800}{\frac{NCV_{Dry\ Fuel}}{100} - 0,2442\ u} \quad [\%] \qquad \text{(Eq. 4-6)}$$

$$\lambda = \frac{21}{21 - O_2 + 0,4\ CO} = \frac{20,4}{CO_2 + CO} \quad [-] \qquad \text{(Eq. 4-7)}$$

$$CO_2 = 0,98(21 - O_2) - 0,61CO \quad [\text{Vol.-\%}] \qquad \text{(Eq. 4-8)}$$

(if O_2 is measured instead of CO_2)

with:				
	T_{Fg}	=	Flue gas temperature	[°C]
	T_A	=	Ambient temperature	[°C]
	O_2	=	Oxygen concentration in dry flue gas	[Vol.-%]
	CO_2	=	Carbon dioxide concentration in dry flue gas	[Vol.-%]
	CO	=	Carbon monoxide concentration in dry flue gas	[Vol.-%]
	$NCV_{Dry\ Fuel}$	=	Net calorific value of absolutely dry fuel (Eq. 4-15)	[kJ kg^{-1}(d.b.)]
	u	=	Humidity of fuel	[wt% (d.b.)]
	λ	=	Excess air ratio	[–]

For a quick visual determination of the combustion efficiency the simplified formula has been transformed into a nomogram (Figure 4.1, valid for $NCV_{Dry\ Fuel}$ = 18'300 kJ kg^{-1}(d.b.).

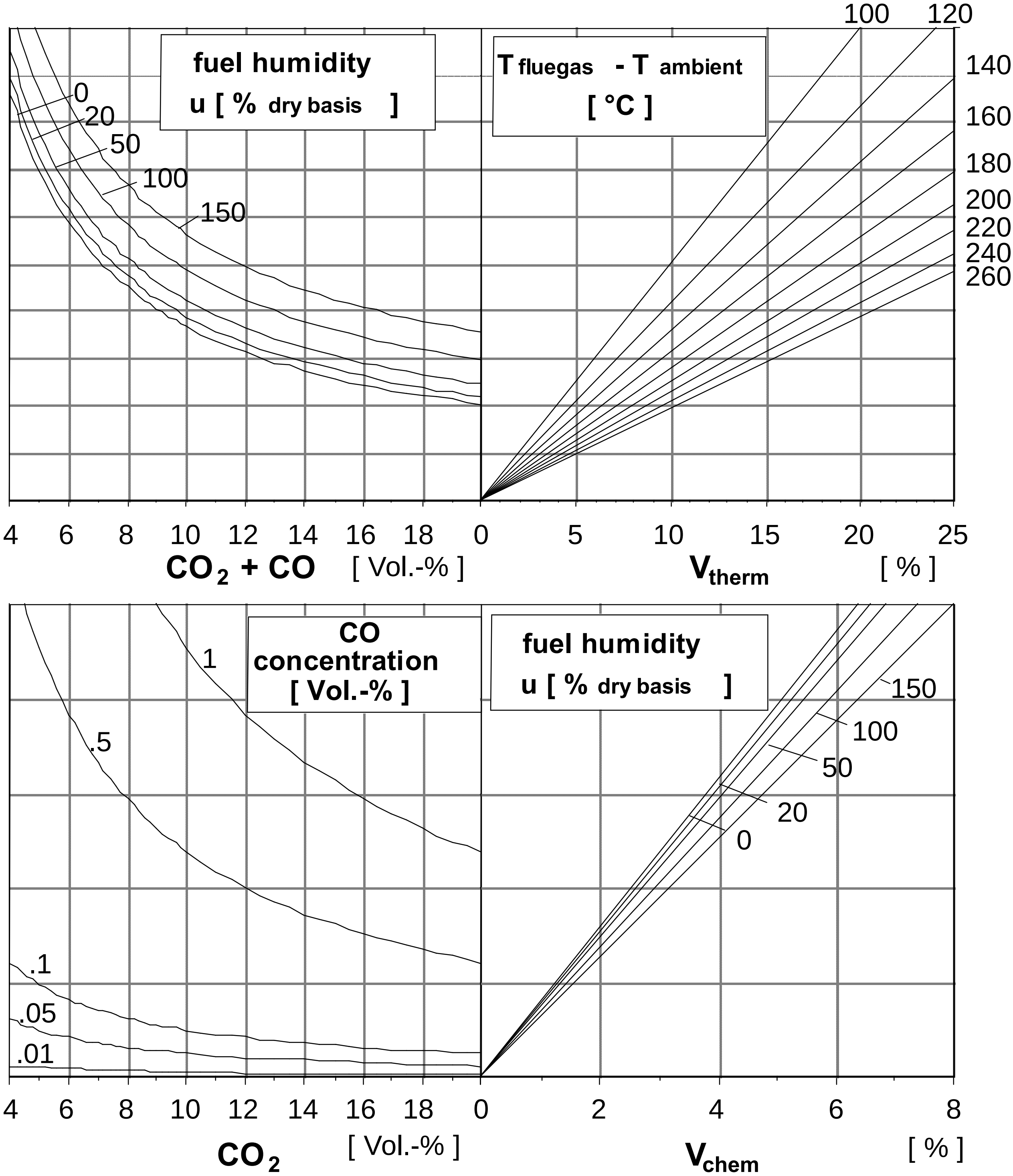


Figure 4.1: Nomogram for the determination of the combustion efficiency according to the simplified formula.

4.3. Boiler Efficiency

4.3.1. Direct Determination Method for Boiler Efficiency

Using the direct determination method, the **boiler efficiency** η_b is defined as follows:

$$\eta_b = 100 \frac{\dot{Q}_{Out}}{\dot{Q}_{In}} = 100 \frac{\dot{Q}_{Calorific\ Fluid}}{\dot{Q}_{Fuel\ Input}} \quad [\%] \qquad \text{(Eq. 4-9)}$$

Where: η_b	=	Boiler efficiency	[%]
$\dot{Q}_{Calorific\,Fluid}$	=	Heat Output through calorific fluid	[kW]
$\dot{Q}_{Fuel\,Input}$	=	Heat input through fuel	[kW]

The heat output through the calorific fluid is expressed as follows:

$$\dot{Q}_{Calorific\,Fluid} = \Delta T_{Fluid}\ c_{p\ Fluid}\ \dot{m}_{Fluid} \quad [\text{kW}] \qquad \text{(Eq. 4-10)}$$

$$\Delta T_{Fluid} = (T_{out} - T_{in}) \quad [°\text{C}] \qquad \text{(Eq. 4-11)}$$

$$\dot{m}_{Fluid} = \dot{V}_{Fluid}\ \rho_{Fluid} \quad [\text{kg/s}] \qquad \text{(Eq. 4-12)}$$

with: T_{out}	=	Temperature of calorific fluid at boiler outlet	[°C]
T_{in}	=	Temperature of calorific fluid at boiler inlet	[°C]
$c_{p\ Fluid}$	=	Specific heat capacity of calorific fluid	[kJ kg^{-1} K^{-1}]
$\dot{m}_{Fluid}$	=	Mass flow of calorific fluid	[kg s^{-1}]
$\dot{V}_{Fluid}$	=	Volume flow of calorific fluid	[m^3 s^{-1}]
ρ_{Fluid}	=	Specific density of calorific fluid	[kg m^{-3}]

The heat input through fuel is expressed as follows:

$$\dot{Q}_{Fuel\ Input} = NCV\ \dot{m}_{Fuel} \quad [\text{kW}] \qquad \text{(Eq. 4-13)}$$

$$NCV = GCV\left(1-\frac{w}{100}\right) - 2442\frac{w}{100} - 2442\frac{h}{100}9.01\left(1-\frac{w}{100}\right) \quad [\text{kJ/kg (w.b.)}] \qquad \text{(Eq. 4-14)}$$

$$NCV_{DryFuel} = GCV - 2442\frac{h}{100}9.01 \quad [\text{kJ/kg (d.b.)}] \qquad \text{(Eq. 4-15)}$$

$$\dot{m}_{Dry\ Fuel} = \dot{m}_{Fuel}\left(1-\frac{w}{100}\right) \quad [\text{kg/s}] \qquad \text{(Eq. 4-16)}$$

NCV	=	Net calorific value of fuel	[kJ kg^{-1}(w.b.)]
$NCV_{Dry\ Fuel}$	=	Net calorific value of absolutely dry fuel	[kJ kg^{-1}(d.b.)]
$\dot{m}_{Fuel}$	=	Mass flow of supplied fuel	[kg s^{-1}]
$\dot{m}_{Dry\ Fuel}$	=	Mass flow of supplied absolutely dry fuel	[kg s^{-1}]
h	=	Hydrogen content of fuel	[wt% (d.b.)]
w	=	Water content of fuel	[wt% (w.b.)]

4.3.2. Indirect Determination Method for Boiler Efficiency

Using the indirect determination method, the **boiler efficiency** η_b is defined as follows:

$$\eta_b = 100 - L_{thermal} - L_{chemical} - L_{rad} - L_{unburnt} + G_{cond} \quad [\%] \qquad \text{(Eq. 4-17)}$$

$$\eta_b = \eta_c - L_{rad} - L_{unburnt} + G_{cond} \quad [\%] \qquad \text{(Eq. 4-18)}$$

Where: η_c	=	Combustion Efficiency	[%]
$L_{thermal}$	=	Thermal losses by sensible heat of dry flue gas	[%]
$L_{chemical}$	=	chemical losses by incomplete combustion	[%]
L_{rad}	=	Thermal losses by radiation, convection and thermal conduction	[%]
$L_{unburnt}$	=	Thermal losses by unburnt fuel (such as unburned carbon in ash residues)	[%]
G_{cond}	=	Thermal gain by condensation of water vapour	[%]

As the investigated biomass combustion plants are non-condensing systems, the thermal gain of condensation of water vapour is not taken into consideration. The thermal losses by unburnt fuel are not taken into consideration. All efficiencies are based on the net calorific value of the fuel.

4.4. Annual Plant Efficiency

4.4.1. Direct Determination Method for Annual Plant Efficiency

Using the direct determination method, the **annual plant efficiency** η_{annual} is defined as follows:

$$\eta_{annual} = 100 \frac{Q_{Out}}{Q_{In}} \quad [\%]$$ (Eq. 4-19)

Where:
- η_{annual} = Annual plant efficiency [%]
- Q_{Out} = Annual produced heat (useful heat output of the boiler) [kWh/a]
- Q_{In} = Annual supplied heat (amount and energy content of supplied fuel) [kWh/a]

The annually produced heat can be measured using a heat meter. To measure the annual supplied heat, the amount of the supplied fuel and its energy content need to be measured for each delivery of fuel. This can be done:

- by weight: measuring the weight in kg (w.b.) and determination of the net calorific value in kJ per kg (w.b.) for each fuel delivery
- by volume: measuring the volume in m^3 bulk and determination of the energy density in kJ per m^3 bulk for each fuel delivery.

4.4.2. Indirect Determination Method for Annual Plant Efficiency

A model for the estimation of the annual plant efficiency has been introduced in [1] as follows:

$$\eta_{annual} = \frac{Q_{Out}}{Q_{In}} = \int_0^{t_{On}} \frac{\dot{Q}_{Out}(t)}{\dot{Q}_{In}(t)} dt = \frac{\int_0^{t_{On}} \dot{Q}_{Out}(t)\, dt}{\int_0^{t_{On}} \dot{Q}_{In}(t)\, dt} = \frac{\sum_0^{t_{On}} \dot{Q}_{Out} \Delta t}{\sum_0^{t_{On}} \dot{Q}_{In} \Delta t} \quad [-]$$ (Eq. 4-20)

$$\eta_{annual} = \frac{annual\,heat\ production}{\frac{annual\,heat\ production}{\eta_b} + \frac{annual\,loss\ during\ \mathrm{standby}}{\eta_b}} \quad [-]$$ (Eq. 4-21)

$$\eta_{annual} = \frac{\dot{Q}_N\ L\ t_{Operating}}{\frac{\dot{Q}_N}{\eta_b} L\ t_{Operating} + \frac{\dot{Q}_N}{\eta_b} q_{Standby}\ t_{Standby}} = \eta_b \frac{L\ t_{Operating}}{L\ t_{Operating} + q_{Standby}\ t_{Standby}} \quad [-]$$ (Eq. 4-22)

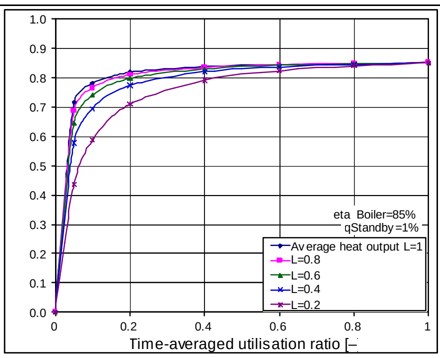
$$\eta_{annual} = \eta_b \frac{1}{1 + \frac{q_{Standby}}{L} \frac{t_{Standby}}{t_{Operating}}} \quad [-]$$ (Eq. 4-23)

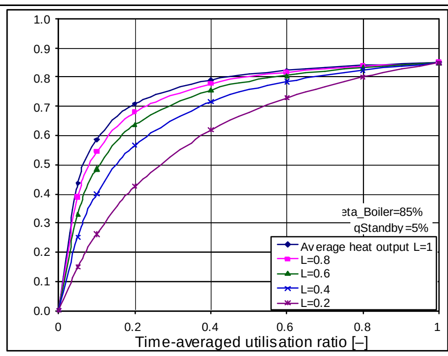
With $\alpha = \frac{t_{Operating}}{t_{On}}$ [–] , $t_{On} = t_{Operating} + t_{Standby}$ and the definitions described in Table 4-2 follows a formula for the estimation of the annual plant efficiency:

$$\boxed{\eta_{annual} = \eta_b \frac{1}{1 + \frac{q_{Standby}}{L} \frac{1-\alpha}{\alpha}} \quad [-]}$$ (Eq. 4-24)

Table 4-2: Definitions of the terms used in the formula for the estimation of the annual efficiency of a biomass furnace.

Variables	**Abbreviation**	**Unit**	**Formula**	**Description**
Annual plant efficiency	η_{annual}	[–]		
Boiler efficiency	η_b	[–]		
Average heat output load	L	[–]	$L = \frac{Q_{Out}}{\dot{Q}_N \, t_{Operating}}$	Indicates the annual average of the heat output load or the load-based utilisation ratio of the boiler
Utilisation ratio	α	[–]	$\alpha = \frac{t_{Operating}}{t_{On}}$	Indicates the time-based utilisation ratio of the boiler
Specific heat losses during standby mode	$q_{Standby}$	[–]	$q_{Standby} = \frac{\dot{Q}_{Standby}}{\dot{Q}_F}$	Based on fuel input load
Annual heat production	Q_{Out}	[kWh/a]		Q_{Out} = heat meter reading at t=t_{On} minus heat meter reading at t=0 (e.g. heat meter reading at the end of the heating period minus heat meter reading at the beginning of the heating period)
Fuel input load	$\dot{Q}_{In}$	[kW]	$\dot{Q}_{In} = \dot{Q}_F = \frac{\dot{Q}_{Out}}{\eta_b}$	
Heat output load	$\dot{Q}_{Out}$	[kW]	$\dot{Q}_{Out} = \dot{Q}_N \, L$	
Nominal heat output load	$\dot{Q}_N$	[kW]		
Total time ON	t_{On}	[h/a]	$t_{On} = t_{Operating} + t_{Standby}$	Annual hours between the boiler is put into operation (e.g. at the beginning of the heating period) and the boiler is put out of operation (e.g. at the end of the heating period)
Total time in operation mode	$t_{operating}$	[h/a]		Annual sum of hours the boiler being in operation mode (e.g. flue gas fan running)
Total time in standby mode	$t_{Standby}$	[h/a]		Annual sum of hours the boiler being in standby mode just keeping itself at temperature (e.g. flue gas fan not running, fuel feeded now and then)





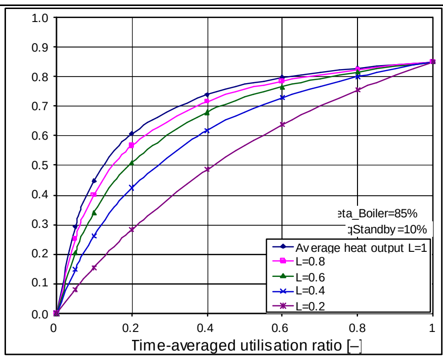


Figure 4.2: Annual plant efficiency as function of the time-averaged utilisation ratio α with boiler efficiency η_B = 85% and specific heat losses during standby mode $q_{Standby}$
= 1% upper left
= 5% upper right
= 10% lower left.

5. Determination of Uncertainty

5.1. Fundamentals

The following uncertainty considerations are based on the EURACHEM/CITAC Guide [5].

The uncertainty $u(y,x_i)$ denotes the uncertainty in y arising from the uncertainty in x_i. Before combination, all contributions from uncertainty components must be expressed in a first step as individual **standard uncertainties**, that is, as standard deviations.

In a second step, the **combined standard uncertainty** $u_c(y)$ is calculated from the individual standard uncertainties. The general relationship between the combined standard uncertainty $u_c(y)$ of a value y and the uncertainty of the **independent** parameters $x_1, x_2, \ldots x_n$ on which it depends is

$$u_c\left(y(x_1, x_2, \ldots)\right) = \sqrt{\sum_{i=1,n} c_i^2 u(x_i)^2} = \sqrt{\sum_{i=1,n} u(y, x_i)^2} \qquad \text{(Eq. 5-1)}$$

where $y(x_1,x_2,\ldots)$ is a function of several parameters $x_1,x_2,\ldots$, c_i is a sensitivity coefficient evaluated as $c_i=\partial y/\partial x_i$, the partial differential of y with respect to x_i and $u(y,x_i)$ denotes the uncertainty in y arising from the uncertainty in x_i.

The final stage is to multiply the combined standard uncertainty by the chosen coverage factor in order to obtain an **expanded uncertainty** U. The expanded uncertainty is required to provide an interval which may be expected to encompass a large fraction of the distribution of values which could reasonably be attributed to the mesurand. Where the distributions concerned are normal, a coverage factor k of 1 gives an interval containing approximately 75% of the distribution of values, whereas a coverage factor k of 2 gives an interval containing approximately 95% of the distribution of values. If really the distributions concerned are normal, this interval is taken to imply a confidence interval or level of confidence of 95%.

$$U = k\, u_c\left(y(x_i)\right) \qquad \text{(Eq. 5-2)}$$

5.2. Combined Standard Uncertainty u_c of Calculated Parameters

The combined uncertainty u_c is calculated using the spreadsheet method described in [5] using a numerical method of differentiation. Table 5-1 illustrates the spreadsheet method, whereas Table 5-2 gives a numerical example.

5.3. Expanded Uncertainty U

As described in section 5.1 the expanded uncertainty U is the combined standard uncertainty multiplied with a coverage factor k. A coverage factor k = 2 is used implying a confidence interval or level of confidence of approximately 95%.

Table 5-1: Spreadsheet method for calculation of the combined standard uncertainty u_c.

Figure E2.3

	A	B	C	D	E
1		u(p)	u(q)	u(r)	u(s)
2					
3	p	p+u(p)	p	p	p
4	q	q	q+u(q)	q	q
5	r	r	r	r+u(r)	r
6	s	s	s	s	s+u(s)
7					
8	y=f(p,q,..)	y=f(p',...)	y=f(..q',..)	y=f(..r',..)	y=f(..s',..)
9		u(y,p)	u(y,q)	u(y,r)	u(y,s)
10	u(y)	$u(y,p)^2$	$u(y,q)^2$	$u(y,r)^2$	$u(y,s)^2$
11					

Table 5-2: Numerical example of the spreadsheet method for the combined standard uncertainty of the net calorific value NCV.

Individual Contribution to Combined Standard Uncertainty of NCV				
		Individual standard uncertainty of		
		GCV	H	w
		+460	+0.16	+2.25
GCV	20'050	20'510	20'050	20'050
H	6.30	6.30	6.46	6.30
w	32.0	32.0	32.0	34.25
NCV	**11'906**	12'219	11'882	11'432
u(NCV,xi)		313	24	475
uc(NCV,xi)	**569**	97'844	575	225'559
			Individual Contribution	
			absolute	% relative
GCV	Gross Calorific Value		313	2.6
H	Hydrogen Content of Fuel		24	0.2
w	Water Content of Fuel		475	4.0
			Combined Standard Uncertainty of NCV	
			absolute	% relative
NCV	Net Calorific Value		569	4.8

6. Plant and Measurement Facilities

6.1. Belgian Biomass Combustion Plant

In the Department of Agricultural Engineering of the Agricultural Research Center-Wallonia (CRA-W) in Gembloux, Belgium, a 550 kW industrial boiler (Schmid/Vyncke) for biomass is installed. The boiler is equipped with water-cooled walls and moving grate. The fuel used for the experiments is from local hardwood. The measurement facilities cover:

- Fuel: Gross calorific value (GCV), hydrogen content, ash content water content, fuel rate of supply
- Calorific fluid: Temperature of boiler inlet and outlet, volumetric flow
- Flue gas: Analysers for O_2, CO_2, CO, CH_4, NO_x, temperatures of ambient air, combustion chamber and flue gas, flue gas velocity (pitot tube and wheel-anemometer)

The boiler and the measurement facilities are used to measure the combustion and boiler efficiency as well as emissions at different operation modes. Direct and indirect methods are used to determine the efficiencies.

Figure 6.1: 550 kW biomass boiler (Schmid/Vyncke) in the Department of Agricultural Engineering of the Agricultural Research Center-Wallonia (CRA-W) in Gembloux, Belgium.

Figure 6.2: Gas analysers used in the Department of Agricultural Engineering of the Agricultural Research Center-Wallonia (CRA-W) in Gembloux, Belgium.

6.2. Swiss Biomass Combustion Plant

In the maintenance area of the highway-police in Sarnen, Switzerland, a 350 kW industrial boiler (Müller) for biomass is installed. The boiler is equipped with an understoker fuel supply system. The fuel used for the experiments is from local hardwood. The measurement facilities cover:

- Fuel: Weight, volume, water content and ratio of hardwood of each fuel delivery
- Boiler: Punctiform measurement of O_2, CO, NO_x, temperatures of ambient air and flue gas, flue gas velocity (pitot tube).

The boiler and the measurement facilities are used to determine the annual plant efficiency using direct and indirect methods.

Figure 6.3: 350 kW biomass boiler (Müller) in the maintenance aerea of the highway-police in Sarnen, Switzerland. Left: Boiler, right: Dust removal system (cyclone).

Figure 6.4: Maintenance area of the highway-police in Sarnen, Switzerland. Left: Wood silo

Figure 6.5: Biomass fuel used (left), glow bed (right) of the understoker boiler.

7. Experimental Results at the Belgian Biomass Combustion Plant

7.1. Overview on Combustion Efficiency, Boiler Efficiency and Emissions at Different Heat Load Levels

Table 7-1 gives an overview on the combustion and boiler efficiency as well as on the emissions at different heat load levels of the experiments on the biomass combustion plant in Belgium. The mean values at stationary conditions at 10%, 30%, 60% and 100% of the heat load of the 550 kW biomass boiler (Schmid/Vyncke) are shown. Calculated values are shown in italic. At 100% of the heat load, additionally to the mean values, the Standard Uncertainty u of the measured variables, the Combined Standard Uncertainty u_c of the calculated variables and the Expanded Uncertainty U of the calculated Efficiencies are indicated.

Table 7-1: Overview on combustion efficiency, boiler efficiency and emissions at different heat load levels of the experiments on the biomass combustion plant in Belgium. The values are based on at least 12 hours of stationary operation for each load level.

Variables	**Boiler operating at**	**10%**	**30%**	**60%**	**100%**					
	Unit	**Value**	**Value**	**Value**	**Value**	u	u_c	U	**Abbr.**	**Equation**
Flue Gas										
O_2	Vol.-%	17.56	14.21	11.72	8.06	*0.10*			O_2	
CO_2 (not used for calculations)	Vol.-%	3.00	6.47	8.97	13.35	*0.03*				
CO	ppm	801	131	124	16	*1*			CO	
CH_4	ppm	26	1	1	7					
Excess Air Ratio (calculated from O_2 and CO)	–	*6.11*	*3.09*	*2.26*	*1.62*		*0.01*		Lambda λ	Eq. 3-7
CO_2 (calculated from O2 and CO)	Vol.-%	*3.32*	*6.65*	*9.09*	*12.68*		*0.10*		*CO_2*	Eq. 3-8
CO	*mg/m_n^3 at 13% O_2*	*2329*	*193*	*133*	*13*					
CH_4	*mg/m_n^3 at 13% O_2*	*43*	*1*	*0*	*3*					
NO_x (NO as NO_2)	*mg/m_n^3 at 13% O_2*	*58*	*99*	*114*	*98*					
Flue Gas Flow (dry, at normal conditions: 25 °C, 1013 mbar)	*m_n^3/h*	*398*	*538*	*685*	*904*					
Flue Gas Flow (dry, at normal conditions: 25 °C, 1013 mbar)	*m_n^3/s*	*0.111*	*0.149*	*0.190*	*0.251*					
Temperatures										
Temperature Flue Gas	°C	85.7	94.0	154.9	189.9	*0.5*			T_{Fg}	
Temperature Ambient Air	°C	27.0	17.0	17.0	17.0	*0.5*			T_A	
Temperature Combustion Chamber	°C	247.9	470.4	679.4	848.2				T_C	
Temperature Calorific Fluid Outlet	°C	72.8	60.9	66.1	74.0				T_{Out}	
Temperature Calorific Fluid Inlet	°C	70.9	53.9	53.7	53.5				T_{In}	
Temperature difference Calorific Fluid Outlet-Inlet	°C	1.96	6.99	12.43	20.45	*0.22*			ΔT_{Fluid}	Eq. 3-11
Temperature difference Calorific Fluid Start-Stop	°C	*8.63*	*-4.49*	*-0.45*	*8.82*					
Calorific Fluid										
Specific Heat Capacity	kJ/(kg K)	3.85	3.85	3.85	3.85	*0.02*			$c_{p\,Fluid}$	
Density	kg/m^3	1060.0	1060.0	1060.0	1060.0	*10.5*			ρ_{Fluid}	
Volumetric Flow	l/min	334.4	334.4	330.0	334.4	*1.8*			$\dot{V}_{Fluid}$	
Mass Flow	*kg/s*	*5.91*	*5.91*	*5.83*	*5.91*		*0.07*		$\dot{m}_{Fluid}$	Eq. 3-12
Heat Output Load	*kW*	*45*	*159*	*279*	*465*		*8*		$\dot{Q}_{Calorific\ Fluid}$	Eq. 3-10
Accumulated Heat Load (calc. for 2300 liter of calorifique fluid) (not added to Useful heat output)	*kW*	*3.6*	*-0.7*	*-0.1*	*1.8*					
Fuel										
Water content	wt% (w.b.)	21.8	29.5	27.7	32.0	*1.80*			w	
Humidity	*wt% (d.b.)*	*27.9*	*41.8*	*38.3*	*47.1*		*2.55*		u	
Hydrogen content	*wt% (d.b.)*	6.3	6.3	6.3	6.3	*0.16*			h	
Ash content	*wt% (d.b.)*	1.0	1.0	1.0	1.0	*0.05*			ash	
Gross Calorifique Value	MJ/kg (d.b.)	20'050	20'050	20'050	20'050	*460*			GCV	
Mass flow	kg/h (w.b.)	18.2	57.0	93.5	179	*7.5*			$\dot{m}_{Fuel}$	
Mass flow of absolutely dry fuel	*kg/h (d.b.)*	*14.2*	*40.2*	*67.6*	*121.7*		*6.0*		$\dot{m}_{Dry\ Fuel}$	Eq. 3-16
Net Calorifique Value	*kJ/kg (w.b.)*	*14'063*	*12'438*	*12'818*	*11'910*		*493*		NCV	Eq. 3-14
Net Calorifique Value of absolutely dry fuel	*kJ/kg (d.b.)*	*18'664*	*18'664*	*18'664*	*18'664*		*461*		$NCV_{Dry\ Fuel}$	Eq. 3-15
Fuel Load	*kW*	*71*	*197*	*333*	*592*		*35*		$\dot{Q}_{Fuel\ Input}$	Eq. 3-13
Boiler										
Losses by radiation and convection	% (2% of full load)	20.0	6.7	3.3	2.0	0.5			L_{rad}	
Efficiency										
Boiler Efficiency (Direct Determination Method)	%	*62.8*	*80.7*	*83.8*	*78.6*		*4.7*	*9.5*	η_b	Eq. 3-9
Boiler Efficiency (Indirect Determination Method)	%	*66.1*	*84.2*	*84.5*	*86.2*		*0.9*	*1.7*	η_b	Eq. 3-18
Combustion Efficiency (Indirect Determination Method)	%	*86.1*	*90.9*	*87.8*	*88.2*		*0.3*	*0.7*	η_c	Eq. 3-4

italic: calculated values
u: Standard Uncertainty
u_c: Combined Standard Uncertainty
U: Expanded Uncertainty (k=2: Level of Confidence - 95%)

7.2. Combustion and Boiler Efficiency Calculated with Direct and Indirect Determination Method

Table 7-2 shows combustion and boiler efficiency calculated with direct and indirect determination method. The combined standard uncertainty u_c and the expanded uncertainty U of the calculated efficiencies as well as the energy input and heat output of the biomass boiler are indicated for different heat load levels.

Discussion: Due to a high expanded uncertainty of the energy input, based on the measured fuel feed rate, the expanded uncertainty of the boiler efficiency calculated with the direct determination method is rather high and constant over the range of the heat output of the biomass boiler.
The expanded uncertainty of the combustion efficiency calculated with the indirect determination method is rather small. Taking into account the estimated thermal losses by radiation and convection, the expanded uncertainty of the combustion efficiency calculated with the indirect determination method is quite small at nominal heat output, but it increases with decreasing heat load.

Table 7-2: Overview on combustion and boiler efficiency calculated with direct and indirect determination method, including Combined Standard Uncertainty and Expanded Uncertainty.

Boiler operating at		**10%**			**30%**			**60%**			**100%**		
		Value	u_c ±abs	U ±abs	Value	u_c ±abs	U ±abs	Value	u_c ±abs	U ±abs	Value	u_c ±abs	U ±abs
Direct Determination Method													
Energy/Fuel input	kW	71	4	7	197	11	22	333	19	37	592	35	70
Heat output	kW	45	5	10	159	5	11	279	6	12	465	8	15
Boiler efficiency	%	**62.8**	7.9	**15.8**	**80.7**	5.3	**10.5**	**83.8**	4.9	**9.8**	**78.6**	4.7	**9.5**
Indirect Determination Method													
Boiler efficiency	%	**66.1**	7.2	**14.4**	**84.2**	2.4	**4.8**	**84.5**	1.3	**2.6**	**86.2**	0.9	**1.7**
Combustion efficiency	%	**86.1**	1.0	**2.0**	**90.9**	0.3	**0.7**	**87.8**	0.4	**0.7**	**88.2**	0.3	**0.7**

u_c: Combined Standard Uncertainty
U: Expanded Uncertainty (k=2: Level of Confidence - 95%)

Figure 7.1 shows the combustion and boiler efficiency calculated with direct and indirect determination method, indicating the range of the expanded uncertainty U for k=2, i.e. confidence level ≈ 95%.

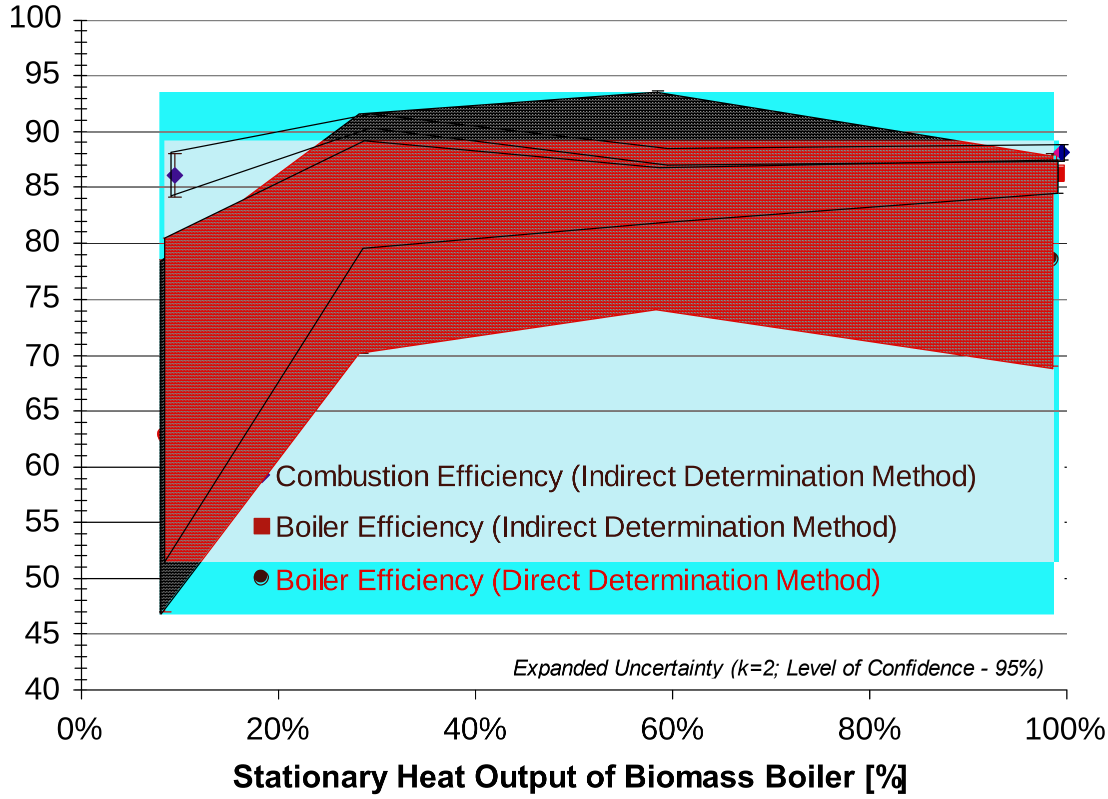


Figure 7.1: Combustion and boiler efficiency at different heat load levels, calculated with direct and indirect calculation method, including expanded uncertainty U for k=2, i.e. confidence level ≈ 95%.

7.2.1. Combustion and Boiler Efficiency calculated with Indirect Determination Method

Figure 7.2 shows the individual contribution of each variable to the combined uncertainty of the combustion efficiency at 100% heat load, calculated with indirect determination method. Figure 7.3 shows the individual contribution of each variable to the combined uncertainty of the boiler efficiency at different heat load levels, calculated with indirect determination method.

Discussion: At high heat load, the combined uncertainty of the combustion efficiency calculated with the indirect determination method is dominated by the uncertainty of the net calorific value at dry base, thus depending mainly from the measured gross calorific value. With decreasing heat load, the contribution of the uncertainty of the oxygen concentration is increasing.

The combined uncertainty of the boiler efficiency calculated with the indirect determination method is dominated by the uncertainty of the estimated thermal losses by radiation, convection and ash.

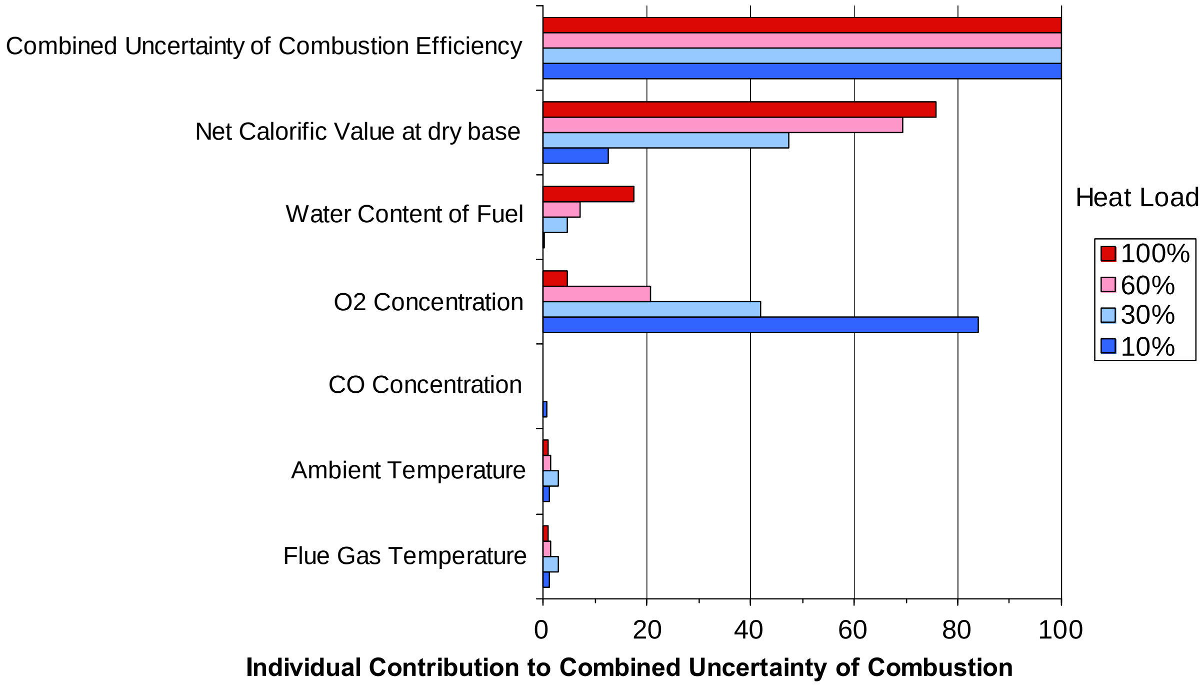


Figure 7.2: Individual contribution of each variable to the combined uncertainty of the combustion efficiency at different heat load levels, calculated with indirect determination method.

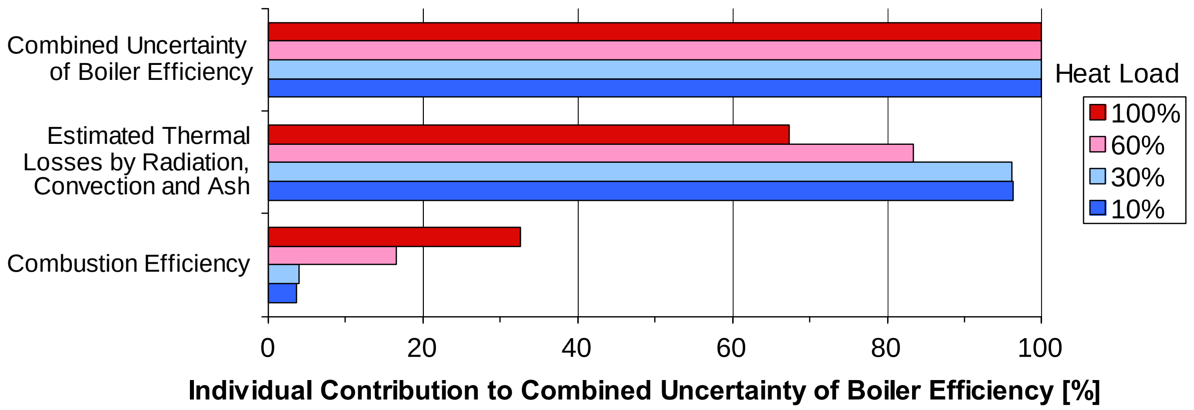


Figure 7.3: Individual contribution of each variable to the combined uncertainty of the boiler efficiency at different heat load levels, calculated with indirect determination method.

7.2.2. Boiler Efficiency Calculated with Direct Determination Method

Figure 7.4 shows the individual contribution of each variable to the combined uncertainty of the combustion efficiency at 100% heat load, calculated with indirect determination method.

Discussion: At high heat load, the combined uncertainty of the boiler efficiency calculated with the direct determination method is dominated by 3 uncertainties, i.e. the uncertainty of the fuel mass flow, the water content and the gross calorific value. Although the fuel mass flow is determined by a calibrated correlation between the speed of the feeding screw and the fuel rate having a small uncertainty of 1.4 kg/h on 100.0 kg/h, the uncertainty during the real samples is estimated to be about 3 times higher (see 'correction factor' in section 7.4) due to the variation of the bulk density and the dimensions and shape of the wood chips in the experiments.

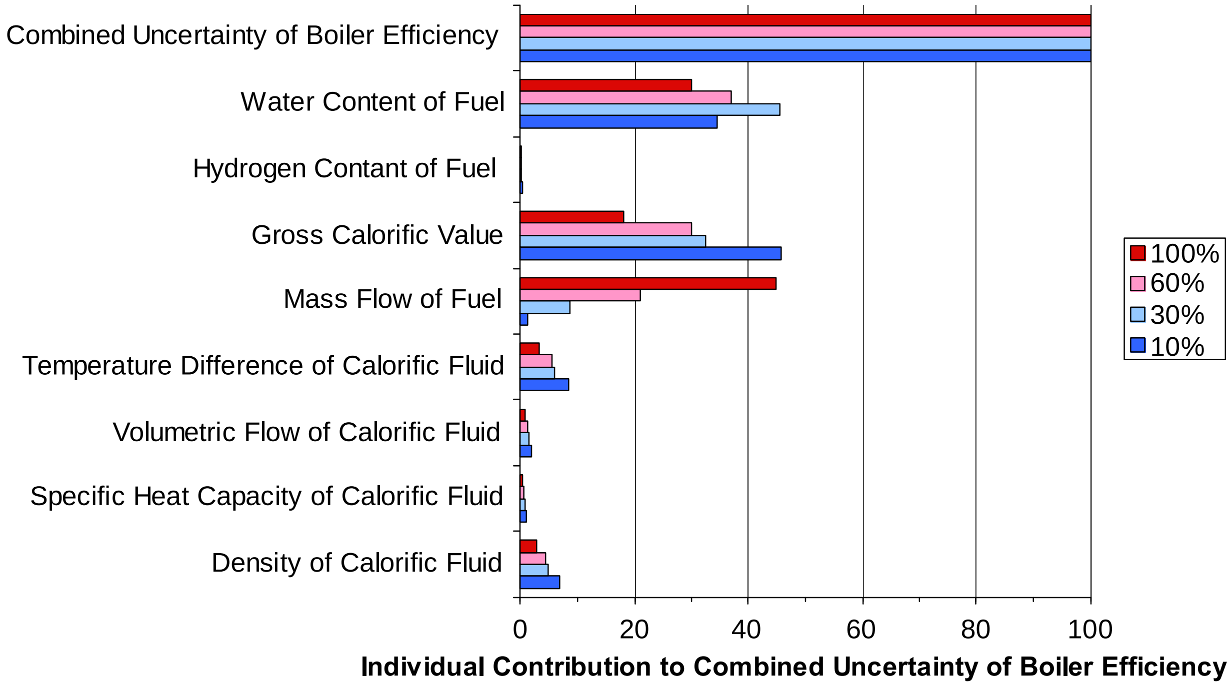


Figure 7.4: Individual contribution of each variable to the combined uncertainty of the boiler efficiency at different heat load levels, calculated with direct determination method.

7.3. Standard Uncertainty of the Investigated Mesurands related to the Uncertainty Determination Method

7.3.1. Overview

Table 7-3 gives an overview on the standard uncertainty of the investigated mesurands related to the determination method. This represents the standard uncertainty of the determination method only, not taking into account the variations of the properties of the fuel, the calorific fluid and the flue gas.

Table 7-3: Overview of the 'Minimum' Standard Uncertainty of the investigated measurands related to the determination method.

Measured Parameters	Unit	Methode of Measurement	Value	'Minimum' Standard Uncertainty u of Method of		Source for Uncertainty
				abs	%rel	
FUEL						
Gross Calorific Value	kJ/kg (d.b.)	Calorimeter	20050	230	1.1	StD of 5 Repetitions
Hydrogen Content	wt% (d.b.)	CHN Analyser	6.3	0.08	1.3	StD of 18 sub-samples
Water Content	wt% (w.b.)	Weighing	32.0	0.90	2.8	StD of 10 sub-samples
Ash Content	wt% (d.b.)	Weighing	1.0	0.05	4.8	StD of 10 sub-samples
Fuel Rate	kg/h	Weighing	100.0	1.40	1.4	StD of 5 Repetitions
CALORIFIC FLUID						
Temperature Boiler Inlet	°C	PT100 Probe	15.9	0.04		StD of 24 Hour Acquisition
Temperature Boiler Outlet	°C	PT100 Probe	15.9	0.02		StD of 24 Hour Acquisition
Temperature Difference	°C		0.0	0.04		StD of 24 Hour Acquisition
Volumetric Flow	l/min	Electromagnetic Flow-Meter (	334.4	0.90	0.3	StD of 17 Hour Acquisition
FLUE GAS						
Temperature Ambient	°C	Mercury Thermometer	17.0	0.10		
Temperature Flue Gas	°C	Thermocouple Type K	17.2	0.10		StD of 24 Hour Acquisition
Temperature Difference	°C		0.1	0.14		StD of 24 Hour Acquisition
Volumetric Flow Flue Gas	Nm3/s	Pitot Tube, Anemometer	0.260	0.020	7.7	StD of 36 Repetitions
CO Concentration	ppm	Uras 14 (Hartmann&Braun)	497	15	3.0	StD of 12 Hour Acquisition
CO2 Concentration	Vol.-%	ZRH100 (Fuji)	10.0	0.01	0.1	StD of 12 Hour Acquisition
O2 Concentration	Vol.-%	Magnos 6G (Hartmann&Braur	8.0	0.05	0.6	StD of 12 Hour Acquisition
NO Concentration	ppm	Uras 14 (Hartmann&Braun)	245	8	3.3	StD of 12 Hour Acquisition
OTHER DATA						
Specific Heat Capacity	kJ/(kg K)		3.85	0.01	0.3	Estimation for StD
Density of Calorific Fluid	kg/m3		1060	7.0	0.7	Estimation from [1]
Condensation Heat of Water	kJ/kg	at 25 °C, 1013 mbar	2442	5	0.2	Estimation for StD

[1] Eurachen Uncertainty Guide

7.3.2. Gross Calorific Value GCV

Acquisition method:
The GCV is determined using Parr calorimeter according to ISO 1928:1995 standard

Uncertainty evaluation:
The Agricultural Research centre of Gembloux is ISO 17025 certified for GCV determination in solid bio fuel. We use the repeatability value obtained during the validation procedure. The obtained standard deviation was 230 kJ/kg (dry basis). We use it as the minimum uncertainty because it was obtained in the best condition: same operator using same material. The sample was a certified raw material and thus its homogeneity was guaranteed by the producer.

7.3.3. Fuel Hydrogen Content

Acquisition method:
The Hydrogen content is determined using CHN analyser (gas chromatography)

Uncertainty evaluation:
The same sample of homogenised milled wood chips have been submitted 18 times to the analyse. The optimum uncertainty is defined as the standard deviation of these 18 values: 0.08 % (dry basis).

7.3.4. Fuel Water Content

Acquisition method:
Water content is determined by drying in oven at 105 °C according to CEN/TS 14774-2.

Uncertainty evaluation:
To determine the standard deviation of the method, 5 kg of 6 months air dried wood chips have been sewed (0.5 cm) and carefully homogenised. Then the sample was divided into 10 sub-samples. Water content has been measured in these 10 sub-samples. The absolute standard deviation is 0.9 % (wet basis). As certified raw material doesn't exist for moisture determination in wood chips, we consider this SD as the minimum uncertainty for the method.

The “real sample” effect:
During prior 550 kW combustion studies, we have measured the water content 19 times during 23 hours. The mean water content is 27.7 % (wet basis) and the absolute standard deviation is 2.2%. It is important to keep in mind the difference between the StD of 0.9% that ONLY represents the uncertainty of water determination method and the SD of 2.2 % that represents the heterogeneity of fuel (and of course also include the uncertainty of the method).

Recently, Nitschke (personal communication) has study methods for determination of moisture of freshly harvested wood chips directly sampled from trucks and observed StD around 5 %.

To take into account the important uncertainty contribution of the “real sample” variation of moisture and in order to study its influence in the boiler yield determination, we will present results calculated with both StD.

7.3.5. Ash content

Acquisition method:
Ash content is determined according to CEN/TS 14775.

Uncertainty evaluation:
The Agricultural Research centre of Gembloux is ISO 17025 certified for ash content determination in solid bio fuel. We use the repeatability value obtained during the validation procedure. The obtained standard deviation was 0.05 % (dry basis). We use it as the minimum uncertainty because it was obtained in the best condition: same operator using same material. The sample was a certified raw material and thus its homogeneity was guarantee by the producer.

7.3.6. Flue Gas Temperature

Acquisition method:
Flue gas temperatures is measured using a K thermocouple and recorded using a data logger

Uncertainty evaluation:
Flue gas temperature has been recorded for 24 hours at a rate of 1 measure per minute, while the boiler was stopped. To avoid the natural “day/night” temperature variation (in our experiment, from 14.8 to 19.5 °C), data were adjusted by subtracting the symmetrical mobile mean. The optimal uncertainty is the standard deviation of the “adjusted” values. The standard deviation is 0.1 °C.

7.3.7. Flue Gas Volumetric Flow

Acquisition method:
The flue gas velocity is measured using both a pitot tube and a digital anemometer at different points in a chimney section. The flue gas volumetric flow is then calculated using the cross section area.

Uncertainty evaluation:
Stack gas flow has been measured 36 times during stationary phase. The average flow rate was 0.26 Nm^3/s and the standard deviation was 0.02 Nm^3/s. This last value is defined as the uncertainty. An additional uncertainty due to variations of the velocity distribution is not taken into consideration.

7.3.8. CO, CO_2, NO and O_2 Concentrations in Flue Gas

Acquisition method:
Oxygen is measured using a Magnos 6G (Hartmann & Braun), CO and NO are analysed using an Uras 14 (Hartman & Braun) and CO_2 is analysed using ZRH100 (Fuji).

Uncertainty evaluation:
To determine the uncertainty associated to each gas concentration, a reference gas has been analysed for one hour. The optimal uncertainty is defined as the standard deviation of all the recorded values and follows (gas reference concentration):associated uncertainty):

CO (497 ppm): 15 ppm

CO_2 (10 %): 0.01 %

NO (245 ppm): 8 ppm

O_2 (8 %): 0.05 %

7.3.9. Calorific Fluid Temperature (In and Out)

Acquisition method:
Calorific fluid temperatures before (“in”) and after (“out”) the boiler are measured using immerged PT100 probes and recorded using a data logger

Uncertainty evaluation:
Temperatures in and out have been recorded for 24 hours at a rate of 1 measure per minute, while the boiler was stopped. To avoid the natural “day/night” temperature variation (in our experiment, from 14.3 to 17.5 °C), data were adjusted by subtracting the symmetrical mobile mean. The optimal uncertainty is the standard deviation of the “adjusted” values. For temperature in and out, the standard deviation are respectively 0.04 and 0.02 °C.

7.3.10. Calorific Fluid Volumetric Flow

Acquisition method:
The calorific fluid volumetric flow is measured using an electromagnetic flow-meter (Promag P, Endress+Hauser)

Uncertainty evaluation:
To determine the uncertainty associated to calorific fluid volumetric flow, the flow has been measured for 17h at 1 measure per minute. The optimal uncertainty is defined as the standard deviation of all the recorded values: 0.9 l/min.

7.3.11. Fuel Rate

Acquisition method:
Fuel rate is determined by weighting wood chips collected during a known period and a known speed of the feeding screw.

Uncertainty evaluation:
Five measurements have been done and the uncertainty is defined as the standard deviation of the five results. For a fuel rate of 100 kg/h (wet), we have measured a standard deviation of 1.4 kg/h.

During the experiments, the fuel rate is calculated from the known speed of the feeding screw.

7.3.12. All Other Data

The uncertainty of following parameters has been assumed to be independent to acquisition and yield calculation method: specific heat of water, condensation heat of water and specific heat of flue gas.

7.4. Standard Uncertainty u(y) of the Investigated Mesurands related to the 'Real' Samples

The variations of the properties of the fuel, the calorific fluid and the flue gas during the 'real' experiments can lead to much higher individual standard uncertainties of the investigated measurands compared to the ones described in the section above. As the property variations are not exactly known, their influence is estimated by multiplying the standard uncertainty related to the determination method with an estimated **Correction Factor**. The values of those correction factors are therefore based on experience only. Table 7-4 gives an overview on the correction factors and the 'real' standard uncertainty of the investigated mesurands for the experiment at nominal heat load of the biomass boiler.

Measured Parameter	Unit	Methode of Measurem	Value	'Minimum' Standard Uncertainty u Method of: abs	%rel	Source for Uncertainty	Value a 100% lo:	Standard Devia StD of DAQ dur experiment: abs	%rel	Source for Uncertainty	Estimated Correction	Standard Uncertainty u 'Real' Measurn: abs	%rel
FUEL													
Gross Calorific Value	kJ/kg (d.b	Calorimeter	20050	230	1.1	StD of 5 Repetitions	20050				*Factor * u of Metho* **2.0**	460	2.3
Hydrogen Content	wt% (d.b.	CHN Analyser	6.3	0.08	1.3	StD of 18 sub-samples	6.3				*Factor * u of Metho* **2.0**	0.16	2.5
Water Content	wt% (w.b	Weighing	32.0	0.90	2.8	StD of 10 sub-samples	32.0				*Factor * u(%) of Met* **2.0**	1.80	5.6
Ash Content	wt% (d.b	Weighing	1.0	0.05	4.8	StD of 10 sub-samples	1.0				*Factor * u(%) of Met* **2.0**	0.10	9.6
Fuel Rate	kg/h	Weighing	100.0	1.40	1.4	StD of 5 Repetitions	179.0				*Factor * u(%) of Met* **3.0**	7.52	4.2
CALORIFIC FLUID													
Temperature Boiler Inlet	°C	PT100 Probe	15.9	0.04		StD of 24 Hour Acquisition	53.5	3.26		StD of 12 Hour Acquisition			
Temperature Boiler Outlet	°C	PT100 Probe	15.9	0.02		StD of 24 Hour Acquisition	74.0	3.13		StD of 12 Hour Acquisition			
Temperature Difference	°C		0.0	0.04		StD of 24 Hour Acquisition	20.5	0.45		StD of 12 Hour Acquisi	*Factor * u of Metho* **5.0**	0.22	1.1
Volumetric Flow	l/min	Electromagnetic Flo	334.4	0.90	0.3	StD of 17 Hour Acquisition	334.4				*Factor * u of Metho* **2.0**	1.80	0.5
FLUE GAS													
Temperature Ambient	°C	Mercury Thermometer	17.0	0.10			17.0	2.0		Estimation			
Temperature Flue Gas	°C	Thermocouple Type K	17.2	0.10		StD of 24 Hour Acquisition	189.9	2.45		StD of 12 Hour Acquisition			
Temperature Difference	°C		0.1	0.14		StD of 24 Hour Acquisition	172.9	3.16		StD of 12 Hour Acquisi	*Factor * u of Metho* **5.0**	0.71	0.4
Volumetric Flow Flue Gas	m3/s	Pitot Tube, Anemomete	0.260	0.020	7.7	StD of 36 Repetitions	0.260				*Factor * u of Metho* **1.5**	0.03	11.5
CO Concentration	ppm	Uras 14 (Hartmann&Bra	[illegible]	15	3.0	StD of 12 Hour Acquisition	164	64		StD of 12 Hour Acqui	*Factor * u(%) of Met* **2.0**	9.90	6.0
CO2 Concentration	Vol.-%	ZRH100 (Fuji)	10.0	0.01	0.1	StD of 12 Hour Acquisition	13.4	0.77		StD of 12 Hour Acqui	*Factor * u(%) of Met* **2.0**	0.03	0.2
O2 Concentration	Vol.-%	Magnos 6G (Hartmar	8.0	0.05	0.6	StD of 12 Hour Acquisition	8.1	0.79		StD of 12 Hour Acqui	*Factor * u(%) of Met* **2.0**	0.10	1.3
NO Concentration	ppm	Uras 14 (Hartmann&Bra	[illegible]	8	3.3	StD of 12 Hour Acquisition	77	7		StD of 12 Hour Acqui	*Factor * u(%) of Met* **2.0**	5.03	6.5
OTHER DATA													
Specific Heat Capacity	kJ/(kg K)		3.85	0.01	0.3	Estimation for StD	3.85				*Factor * u of Metho* **1.5**	0.015	0.4
Density of Calorific Fluid	kg/m3		1060	7.0	0.7	Estimation from [1]	1060				*Factor * u of Metho* **1.5**	10.5	1.0
Condensation Heat of Water	kJ/kg	at 25 °C, 1013 mbar	2442	5	0.2	Estimation for StD	2447				*Factor * u of Metho* **1.0**	5	0.2

[1] Eurachen Uncertainty Guide
DAQ: Data Acquisition
StD: Standard Deviation

Table 7-4: Overview on the estimated correction factors and the resulting 'real' standard uncertainty of the investigated measurands for the experiment at nominal heat load (100%) of the biomass boiler.

7.5. Emissions

The following figures show the concentrations of flue gas components and the excess air ratio of the biomass boiler at different heat load levels, each operated at stationary combustion conditions.

Discussion: Stationary operation at a heat load level of 10 % is, as expected, not suitable for this biomass boiler due to high CO emissions and high excess air ratio, i.e. low efficiency. Between a heat load level of 30 % to 100%, the emissions are quite low.

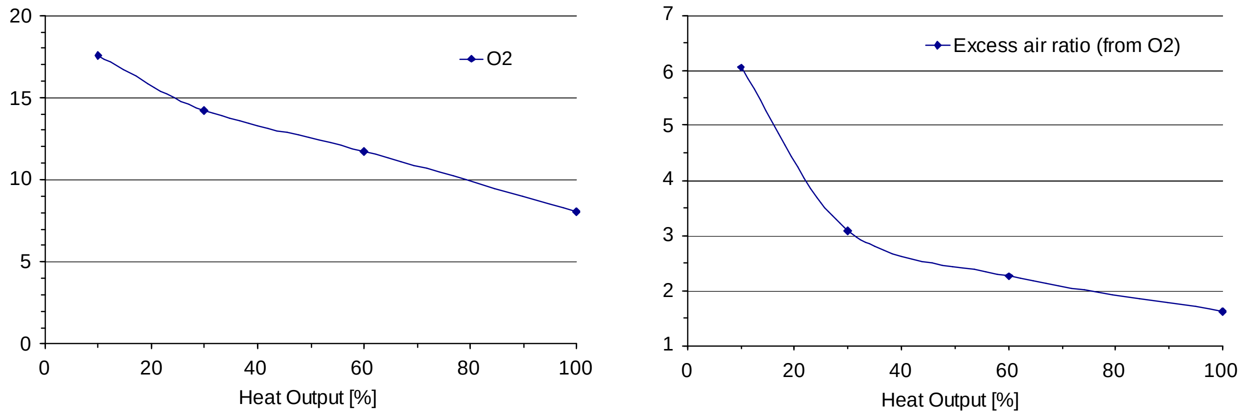


Figure 7.5: Oxygen concentration (O_2) and excess air ratio (lambda) at different heat load levels.

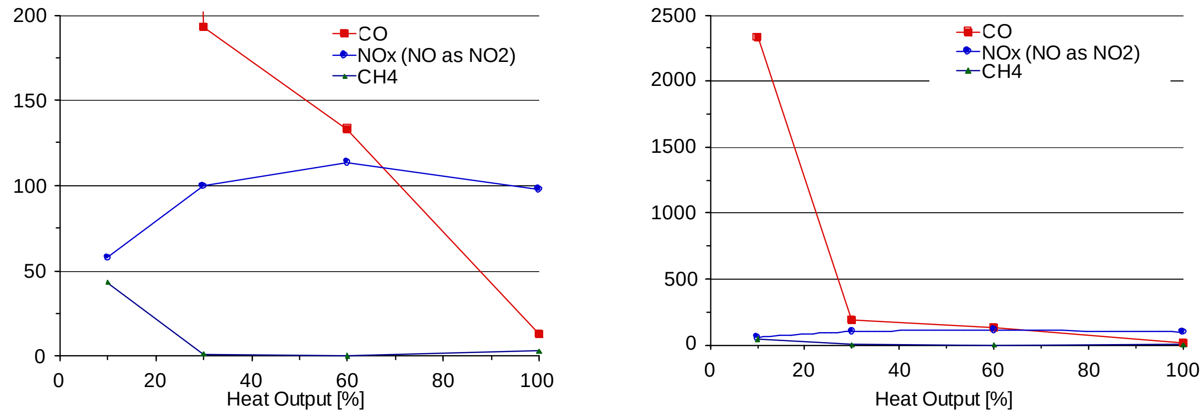


Figure 7.6: CO, NO_x (NO as NO_2), and CH_4 concentration at different heat load levels in two different scalings.

8. Experimental Results at the Swiss Biomass Combustion Plant

8.1. Overview on Annual Plant Efficiency

The experiments were performed on the biomass combustion plant in Switzerland (see section 6.2). For the direct determination method, the annually produced heat was measured by a heat meter, whereas weight, volume, fraction of hardwood and water content of each fuel delivery was measured. For the indirect determination method, all the variables needed (see Table 4-2) were measured or estimated.

Discussion: The expanded uncertainty of both direct determination methods, based on fuel weight and on fuel volume, is much higher than the expanded uncertainty of the indirect determination method. This high uncertainty is dominated by the uncertainty of the energy content of the burnt fuel, i.e. the net calorific value in kWh/kg and the energy density in kWh/m3 bulk (w.b.). Even high-precision weighing cannot help.

Table 8-1: Overview on annual plant efficiency calculated with direct and indirect determination method, including Combined Standard Uncertainty and Expanded Uncertainty.

		Value	u_c ±abs	U ±abs
Direct Determination Method Based on Fuel Weight				
Annual Heat output	MWh/a	823	13	26
Energy Content of burnt Fuel	MWh/a	1050	70	141
Annual Plant Efficiency	**%**	**78.4**	5.1	**10.1**
Direct Determination Method Based on Fuel Volume				
Heat output	MWh/a	823	13	26
Energy Content of burnt Fuel	MWh/a	1014	83	166
Annual Plant Efficiency	**%**	**81.1**	6.3	**12.5**
Indirect Determination Method				
Annual Plant Efficiency	**%**	**80.6**	2.8	**5.6**

u_c: Combined Standard Uncertainty
U: Expanded Uncertainty (k=2: Level of Confidence - 95%)

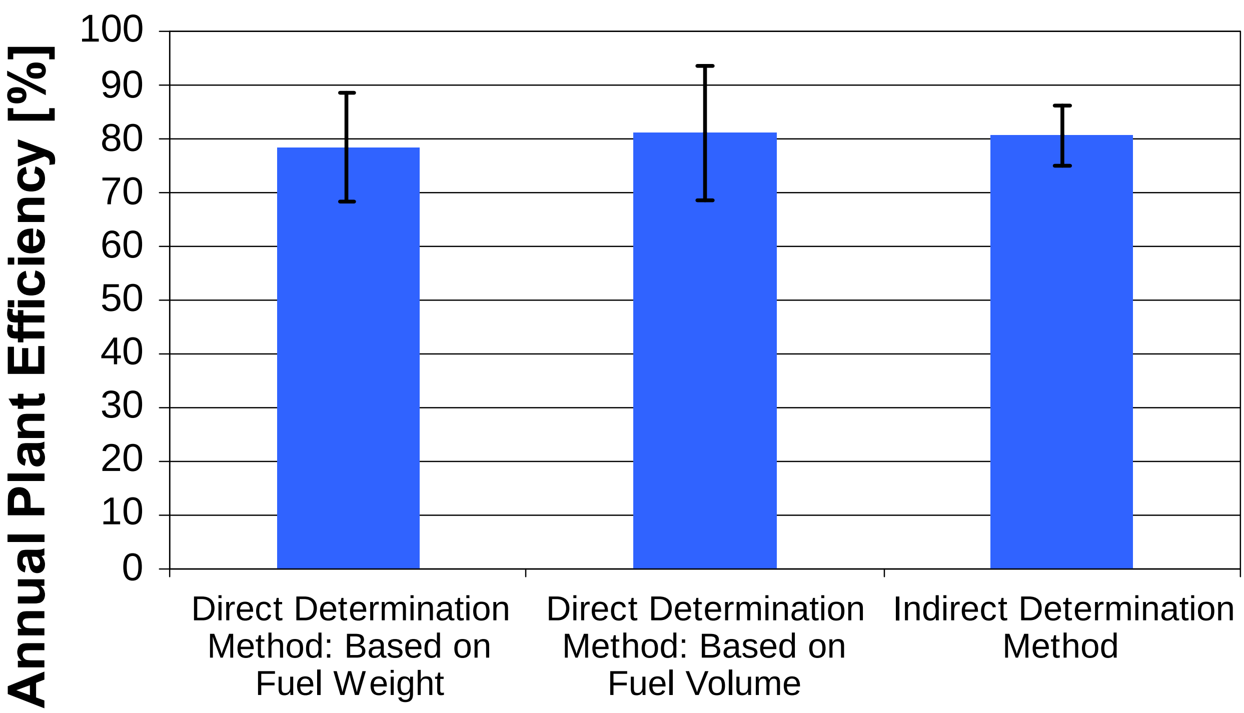


Figure 8.1: Annual plant efficiency calculated with direct determination method, based on fuel weight and on fuel volume, and calculated with indirect determination method.

8.2. Annual Plant Efficiency with Direct Determination Method

8.2.1. Based on Fuel Weight

Table 8-2 gives an overview on the measured and calculated parameters. Additionally to the parameters, it includes the estimated and calculated standard uncertainties. As the fuel sample used for water content determination has only a limited representativity of the real fuel, an estimated **Correction Factor** multiplies the uncertainty of the water content determination. An estimated Correction Factor also multiplies the specified uncertainty of the heat meter. This takes into consideration that the uncertainty of the heat meter can increase for very small temperature differences or for very small flow rates of the fluid. The values of those correction factors are based on experience only.

Discussion: Even with high-precision weighing of the fuel, the uncertainty of the net calorific value and of the water content dominate the uncertainty of the annual plant efficiency.

Table 8-2: Overview on the standard uncertainty of the investigated measurands and calculated parameters for the direct determination method of the annual plant efficiency including estimated correction factors. Based on fuel weight.

Measured Parameters	Unit	Methode of Mea	Value	'Minimum' Standard Uncertainty u of Method abs	'Minimum' Standard Uncertainty u of Method %rel	Source for Uncertainty	Estimated Correction Factor		Value	Standard Uncertainty of 'Real' Measurment abs	Standard Uncertainty of 'Real' Measurment %rel
ANNUAL FUEL DELIVERY (= 9 deliveries)											
Fuel Weight	kg (w.b.)	Calculation	385'230	69	0.02	Calculated			385'230	69.1	0.02
Water Content	wt% (w.b.)	Weighing	40.7	1.50	3.7	Estimation	*Factor * u(%) of Method*	**2.0**	40.7	3.00	7.4
Ratio of hardwood	wt%	Estimation	54.0	5.00	9.3	Estimation			54.0	5.00	9.3
NCV of absolute dry Hardwood	kJ/kg (d.b.)	Estimation	18'100	450	2.5	Estimation			18'100	450.0	2.5
NCV of absolute dry Softwood	kJ/kg (d.b.)	Estimation	19'000	450	2.4	Estimation			19'000	450.0	2.4
NCV of absolute dry wood delivered	kJ/kg (d.b.)	Calculation	18'514	322	1.7	Calculated			18'514	322.4	1.7
NCV of delivered wood	kJ/kg (w.b.)	Calculation	9'985	367.9	3.7	Calculated			9'985	657.1	6.6
Energy Content of delivered Wood	MWh	Calculation	1'068	39.4	3.7	Calculated			1'068	70.3	6.6
HEAT METER											
Energy produced	MWh	Heat meter	823.0	6.42	0.78	Specifications	*Factor * u(%) of Method*	**2.0**	823.0	12.84	1.6
ANNUAL PLANT EFFICIENCY											
Energy produced	MWh	Heat meter	823.0	6.42	0.78	Specifications	*Factor * u(%) of Method*	**2.0**	823.0	12.84	1.6
Energy Content of burned Wood	MWh	Calculation	1'050	39.4	3.8	Calculated			1'050	70.3	6.7
Annual Plant Efficiency	%	Calculation	78.4	2.9	3.7	Calculated			78.4	5.1	6.5

8.2.2. Based on Fuel Volume

Table 8-3 gives an overview on the measured and calculated parameters. Additionally to the parameters, it includes the estimated and calculated standard uncertainties. An estimated **Correction Factor** multiplies the specified uncertainty of the heat meter. This takes into consideration that the uncertainty of the heat meter can increase for very small temperature differences or very small flow rates of the fluid. The value of the correction factor is based on experience only.

Discussion: As expected, the high uncertainty of the energy density dominates the uncertainty of the annual plant efficiency.

Table 8-3: Overview on the standard uncertainty of the investigated measurands and calculated parameters for the direct determination method of the annual plant efficiency including estimated correction factors. Based on fuel volume.

Measured Parameters	Unit	Methode of Mea	Value	'Minimum' Standard Uncertainty u of Method abs	'Minimum' Standard Uncertainty u of Method %rel	Source for Uncertainty	Estimated Correction Factor		Value	Standard Uncertainty of 'Real' Measurment abs	Standard Uncertainty of 'Real' Measurment %rel
ANNUAL FUEL DELIVERY (= 9 deliveries)											
Fuel Volume	m^3	Calculation	1'146	8.2	0.7	Calculated			1'146	8.2	0.7
Ratio of hardwood	wt%	Estimation	54.0	5.0	9.3	Estimation			54.0	5.0	9.3
Energy density of Hardwood (w=40 wt	kWh/m^3 bulk	Estimation	1000	100.0	10.0	Estimation			1000	100.0	10.0
Energy density of Softwood (w=40 wt%	kWh/m^3 bulk	Estimation	750	100.0	13.3	Estimation			750	100.0	13.3
Energy density of delivered wood	kWh/m^3 bulk	Calculation	885	72.0	8.1	Calculated			885	72.0	8.1
Energy Content of burned Wood	MWh	Calculation	1'014	82.9	8.2	Calculated			1'014	82.9	8.2
HEAT METER											
Energy produced	MWh	Heat meter	823	6.4	0.8	Specifications	Factor * u(%) of Method	**2.0**	823	12.8	1.6
ANNUAL PLANT EFFICIENCY											
Energy produced	MWh	Heat meter	823	6.4	0.8	Specifications			823	12.8	1.6
Energy Content of burned Wood	MWh	Calculation	1'014	82.9	8.2	Calculated			1'014	82.9	8.2
Annual Plant Efficiency	%	Calculation	81.1	6.2	7.6	Calculated			81.1	6.3	7.7

8.3. Indirect Determination Method for Annual Plant Efficiency

Table 8-4 and Table 8-5 give an overview on the measured, estimated and calculated parameters. The 'annual mean' values for the calculation of the combustion efficiency are based on measurements at full load, medium load and small load. With the knowledge of the annual operation hours of those three operation modes, the mean values has can be calculated.

Discussion: With realistic estimation of the uncertainties of its parameters, the annual plant efficiency is calculated with reasonable effort and uncertainty.

Table 8-4: Overview on the parameters needed for the indirect determination of the annual plant efficiency and its uncertainties.

Variables	Unit	Value	u	u_c	U	Abbr.	Equation
Flue Gas							
O_2	Vol.-%	12.0	*1.50*			O_2	
CO	Vol.-%	0.010	*0.002*			CO	
CO_2 (calculated from O2 and CO)	Vol.-%	*8.8*		*1.47*		*CO_2*	Eq. 3-8
Excess Air Ratio (calculated from O_2 and CO)	–	*2.34*		*0.47*		Lambda λ	Eq. 3-7
Temperatures							
Temperature Flue Gas	°C	170.0	*10.0*			T_{Fa}	
Temperature Ambient Air	°C	20.0	*3.0*			T_A	
Fuel							
Water content	wt% (w.b.)	40.7	*5.0*			w	
Humidity	*wt% (d.b.)*	*68.5*		*7.1*		u	
Net Calorifique Value of absolutely dry fuel	kJ/kg (d.b.)	18'500	250			$NCV_{Dry\ Fuel}$	Eq. 3-15
Net Calorifique Value	*kJ/kg (w.b.)*	*9'959*		*523*		NCV	Eq. 3-14
Boiler							
Nominal heat output load	kW	350	50			$\dot{Q}_N$	
Heat Losses by radiation and convection	% of full load	2.0	0.5			L_{rad}	
Combustion Efficiency (Indirect Determination Method)	%	85.1		2.8		η_c	Eq. 3-4
Boiler Efficiency (Indirect Determination Method)	%	*83.1*		*2.8*		η_b	Eq. 3-18
Heat Losses during standby mode	% of full load	5.0	1.00			L_{rad}	
Annual heat production	MWh/a	823	13			Q_{Out}	
Total time ON (Operation and Standby mode)	h/a	5'527	28			t_{On}	
Total time in operation mode	h/a	4'082	20			$t_{Operating}$	
Average heat output load	%	58	8.3			L	
Utilisation ratio (timebased)	%	74	0.5			$t_{Operating}$	
Efficiency							
Annual Plant Efficiency (Indirect Determination Method)	%	*80.6*		*2.8*	*5.6*	η_c	Eq. 3-24

italic: calculated values
u: Standard Uncertainty
u_c: Combined Standard Uncertainty
U: Expanded Uncertainty (k=2: Level of Confidence - 95%)

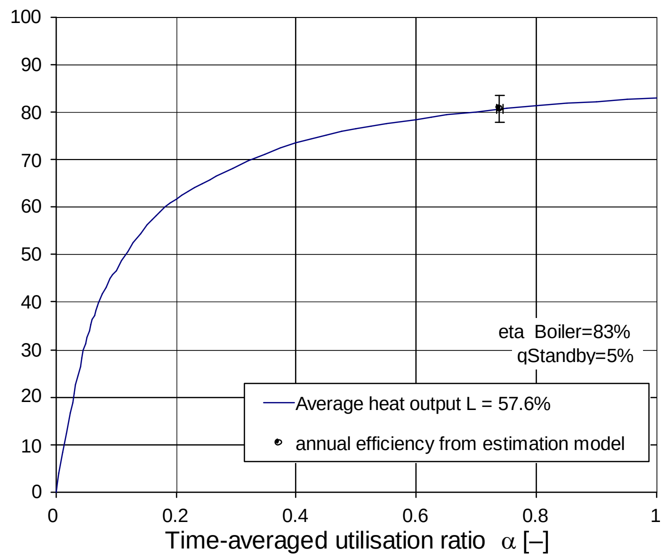


Figure 8.2: Annual plant efficiency of biomass combustion plant in Switzerland calculated with indirect determination method.

Table 8-5: Overview on the parameters needed for the indirect determination of the annual plant efficiency and its uncertainties.

Measured Parameters	Unit	Methode of Measurement	Value	Standard Uncertainty u abs	%rel	Source for Uncertainty
FUEL						
NCV of absolute dry wood	kJ/kg (d.b.)	Estimation	18'500	250	1.4	Estimation
Water Content	wt% (w.b.)	Weighing	40.7	5.00	12.3	Estimation
Net calorific value	kJ/kg (w.b.)	Calculation	9959.3	523.12	5.3	Calculation
FLUE GAS						
Temperature Ambient	°C	PT100 probe	170.0	10.00		Estimation
Temperature Flue Gas	°C	PT100 probe	20.0	3.00		Estimation
O2 Concentration	Vol.-%	O2 Analyser	12.0	0.50	4.2	Estimation
BOILER						
Nominal heat output load	kW	Estimation	350	50	14.3	Estimation
Heat Losses by radiation and convection	% of full load	Estimation	2.0	0.5	25.0	Estimation
Combustion Efficiency (Indirect Determination Method)	%	Calculation	85.1	2.78	3.3	Estimation
Boiler Efficiency (Indirect Determination Method)	%	Calculation	83.1	2.8	3.4	Estimation
Heat Losses during standby mode	% of full load	Estimation	5.0	1.0	20.0	Estimation
Annual heat production	MWh/a	Heat meter	823	13.2	1.6	2 * Specifications
Total time ON (Operation and Standby mode)	h/a	Estimation	5'527	28	0.5	Estimation
Total time in operation mode	h/a	Estimation	4'082	20	0.5	Estimation
Average heat output load	%	Calculation	57.6	8.3	14.4	Estimation
Utilisation ratio (timebased)	%	Calculation	73.9	0.5	0.7	Estimation
BOILER						
Annual Plant Efficiency (Indirect Determination Method)	%	Calculation	80.6	2.8	3.5	Estimation

9. Conclusions

9.1. Results from test-bench

1. The indirect determination method for the Combustion Efficiency is very accurate (< 1%) for the whole heat load range of 30% to 100%.
2. The indirect determination method for the Boiler Efficiency is accurate (< 3%) for the heat load range of 50% to 100%.
3. The direct determination method for the Boiler Efficiency, i.e. heat output divided by energy input, leads to high uncertainty (> 10%) mainly caused by the uncertainty of the fuel mass flow at the test-bench.

9.2. Results from practical plant

1. The indirect determination method for the Annual Plant Efficiency, i.e. the formula proposed for fuel accounting, is relatively accurate (< 6%) if the boiler efficiency is known and the operation of the plant is reasonable.
2. The direct determination method for the Annual Plant Efficiency, i.e. heat output divided by energy input, based on highly accurate fuel mass, leads to high uncertainty (> 10%) mainly caused by the uncertainty of the net calorific value and of variations of the water content of the fuel at the practical plant.
3. The direct determination method for the Annual Plant Efficiency, i.e. heat output divided by energy input, based on fuel mass, is slightly more accurate than based on fuel volume in case of well known fuel type and bulk density. It is far more accurate than based on fuel volume in case of varying fuel type without well-known net calorific value and bulk density.
4. The indirect determination method for the Annual Plant Efficiency is an interesting method for fuel accounting in case of one single fuel supplier, as it is cheaper and more accurate than fuel mass measurement only.
5. The indirect determination method for the Annual Plant Efficiency, i.e. the formula proposed for fuel accounting, could not be validated due to the higher uncertainty of the reference method, i.e. the direct determination method for the Annual Plant Efficiency, i.e. heat output divided by energy input, based on fuel mass.

9.3. Results on emissions and efficiency of grate combustion

1. The investigated grate boiler (test-bench)
   - enables high efficiency and low emissions for the whole heat load range from 30% to 100%
   - achieves low efficiency and high emissions at 10% heat load.
2. The comparison of different part-load operation modes needs further investigations.

10. References

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