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DETERMINATION OF THE COMBUSTION EFFICIENCY IN BIOMASS FURNACES

Th. Nussbaumer[1,2] and J. Good[2]
[1]Swiss Federal Institute of Technology, ETH Zurich, CH - 8092 Zurich, Switzerland
[2]Verenum Research, Langmauerstrasse 109, CH - 8006 Zurich, Switzerland
Phone: +41 1 364 14 12, Fax: +41 1 364 14 21, Email: verenum@access.ch

ABSTRACT: The combustion efficiency is the main parameter to describe the performance of a biomass furnace. Since there is no standard method to determine the efficiency, the data from different test laboratories cannot be compared without uncertainties. The aim of the present study is to develop an accurate determination method for the combustion efficiency for different biofuels. Furthermore the results with the proposed method should be compared with typical calculation methods used nowadays.
To evaluate an accurate formula for the combustion efficiency, the biomass composition is used to describe the mass balance and calculate the flue gas composition. By describing the energy balance from fuel to flue gas and using the physical properties of the different gas components, an exact formula for the determination of the combustion efficiency is evaluated. For an easier application, a simplified formula is developed which can easily be used in data acquisition programs or on pocket calculators and which only leads to an error < 0.2 % in comparison to the exact formula.
It is shown that the formula from DIN 4702 gives similar results for wood as the new method, while the other tested formulas can lead to significant errors. For wood furnaces, either the new formula or the DIN formula can be used, while for all other biofuels, the new formula can be adapted if the fuel composition is known. The new formula is proposed for all applications to guarantee an understandable calculation with well known assumptions. For most purposes in biomass combustion, the simplified formula which is described in the paper and illustrated in a nomogram can be used.
Keywords: combustion efficiency, standardization, energy balance, CO_2-content

1. INTRODUCTION

The combustion efficiency is the main parameter to describe the performance of a biomass furnace. Therefore a correct determination of the efficiency is essential for a comparison of furnaces. Several calculation methods which use distinct assumptions can be found in the literature and different test laboratories for biomass furnaces use their own methods to determine the thermal and chemical losses [1].
One of the commonly used formulas is according to DIN 4702. This formula gives good results for wood. However the assumptions for the calculation are not known. Therefor it is not possible to transform the formula for biofuels with other compositions. Furthermore the formula is not very suitable for computational application in field measurements.
A comparison between DIN and two other formulas showed that at a high CO content in the flue gas the calculation methods can lead to different results [2], while in some cases the differences are not significant. However the application of different formulas is not satisfying and the interpretation of the results often leads to discussions which could be avoided if a standardized formula was used. Furthermore the derivation of the different methods is not transparent enough.

The aim of the present study was to develop an accurate determination method for the combustion efficiency which can be used for different biofuels and fulfills the following conditions:

- The derivation of the formula has to be transparent
- A simplified formula which is easy to use and leads to accurate results for a typical biomass composition should be presented
- For fuels which differ significantly from typical biomass, the method should be applicable if the detailed composition is known.

Furthermore the results of the new method should be compared with the formulas used nowadays according to DIN in Germany, EMPA in Switzerland and BLT in Austria [1,3,4]. The new formula is proposed as standard method for future application.

2. MASS AND ENERGY BALANCE

To derive an accurate formula for the combustion efficiency, the biomass composition is used to describe the combustion reaction as follows (see also [5] and [6]):

$$\mathbf{CH_mO_n} + \frac{u}{100}\frac{M_{Biomass}}{M_{Water}}\mathbf{H_2O} + \lambda A\left(\mathbf{O_2} + \frac{79}{21}\mathbf{N_2}\right) \rightarrow$$

$$(1-\beta)\,\mathbf{CO_2} + \beta\,\mathbf{CO} + \left(\frac{m}{2} + \frac{u}{100}\frac{M_{Biomass}}{M_{Water}}\right)\mathbf{H_2O} + \left((\lambda-1)A + \frac{b}{2}\right)\mathbf{O_2} + \lambda A\frac{79}{21}\mathbf{N_2}$$

with:

A	=	Fuel constant for CH_mO_n	$= 1 + m/4 - n/2$
u	=	fuel humidity on dry basis	[%]
$M_{Biomass}$	=	molar weight of wood $CH_{1.44}O_{0.66}$	$= 24.0$ kg kmol^{-1}
M_{Water}	=	molar weight of water	$= 18.0$ kg kmol^{-1}
CO_2	=	concentration of CO_2 in the dry flue gas	[Vol.-%]
CO	=	concentration of CO in the dry flue gas	[Vol.-%]
β	=	$\frac{CO}{CO + CO_2}$	

The method is based on the following assumptions:

- hydrocarbons and soot in the flue gas is neglected
- the flue gas components behave like an ideal gas
- the typical composition of wood is assumed to be: CH_mO_n with $m = 1.44$ and $n = 0.66$
- the combustion air consists of 21 Vol.-% O_2 and 79 Vol.-% N_2
- the humidity of the combustion air is neglected
- NO_x emissions are neglected
- the excess air ratio is ≥ 1
- the heating value on dry basis is $h_u = 18'500$ kJ kg^{-1}.

From the presented reaction scheme the composition of the flue gas can be calculated for different biofuels. By describing the energy balance from fuel to flue gas and using the physical properties (heat capacity, density) of the different flue gas components, an accurate formula for the determination of the combustion efficiency is evaluated. The detailed derivation of the exact formula is presented in [2]. The exact formula needs a certain effort for application.

3. COMPARISON OF DIFFERENT FORMULAS WITH EXACT FORMULA

The formula from DIN 4702 gives similar results for wood as the exact formula [2], while the other tested formulas can lead to significant errors.

For wood furnaces, either the new formula or the DIN formula can be used, while for all other biofuels, the new formula can be adapted if the composition of the fuel is known. However the new formula is proposed for all applications to guarantee an understandable calculation with well known assumptions. A high accuracy is achieved for flue gas temperatures < 400 °C, CO < 0.5 % vol. and CO_2 > 5 % vol..

4. SIMPLIFIED FORMULA

For an easier application, a simplified formula with sufficient accuracy is needed which can easily be used in data acquisition programs or on pocket calculators. The following simplifications of the exact formula lead to a simplified formula which results in an error < 0.2 % in comparison to the detailed formula (Fig. 1):

- CO is neglected in the combustion reaction
- the excess air ratio is assumed as $\lambda = 20.4 / (CO_2 + CO)$
- the specific heat capacities of the flue gas components are considered constant being the mean value in the temperature range of 0 – 200 °C

For a quick visual determination of the combustion efficiency the simplified formula has been transformed into a nomogram (Fig. 2).

$$\eta_f = 100 - V_{therm} - V_{chem} \quad [\%]$$

where:

- η_f = combustion efficiency
- V_{therm} = thermal losses of the flue gas
- V_{chem} = chemical losses of the flue gas

with:

$$V_{therm} = \frac{(T_A - T_U)\left\{1.39 + \frac{122}{CO_2+CO} + 0.02\,u\right\}}{\frac{h_{u\,atro}}{100} - 0.25\,u} \quad [\%]$$

$$V_{chem} = \frac{CO}{CO_2+CO}\,\frac{11'800}{\frac{h_{u\,atro}}{100} - 0.25\,u} \quad [\%]$$

and:

- T_A = flue gas temperature [°C]
- T_U = ambient temperature [°C]
- CO, CO_2, O_2: concentrations in [Vol.-%]
- u = fuel humidity on dry basis [%]
- $h_{u\,atro}$ = heating value of dry wood = 18'500 [kJ kg^{-1}]

If O_2 is measured inspite of CO_2, CO_2 is calculated as follows:

$$CO_2 = 0.98\,(21 - O_2) - 0.61\,CO \quad [\text{Vol.-\%}]$$

Figure 1: Simplified formula for the determination of the combustion efficiency for typical wood.

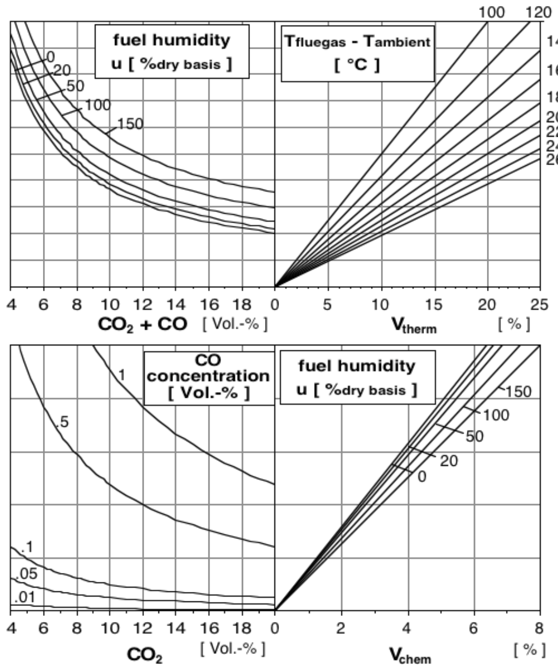

Figure 2: Nomogram for the determination of the combustion efficiency according to the presented method.

5. CONCLUSIONS

The combustion efficiency is the main parameter to describe the performance of a biomass furnace. Many test laboratories for biomass furnaces use their own methods to determine the thermal and chemical losses of the flue gas. The derivation of those methods is not transparent and they cannot be used for other biofuels.

A new method for the calculation of the combustion efficiency has been determined. The method is based on the combustion reaction and therefore can be applied to every biofuel with given composition.

For a typical wood composition an exact formula has been developed by describing the energy balance from fuel to flue gas and using the physical properties of the different gas components. With the same method, an exact formula for any given fuel composition can be derived.

With minor modifications of the exact formula, a simplified formula has been developed which gives accurate results for typical flue gas temperatures and compositions. The simplified formula is easy to use for data acquisition or pocket calculators. With the presented nomograms the combustion efficiency can also be determined graphically. The formula according to DIN 4702 leads to similar results. However DIN cannot be transformed for other compositions and it is not very suitable for computational applications. Two other formulas used nowadays can lead to minor errors and are therefore not proposed for future use.

The presented formula can easily be adapted for other biofuels and it is proposed as standard method for the determination of combustion efficiencies in future. For usual purposes, the application of the simplified method is favourable.

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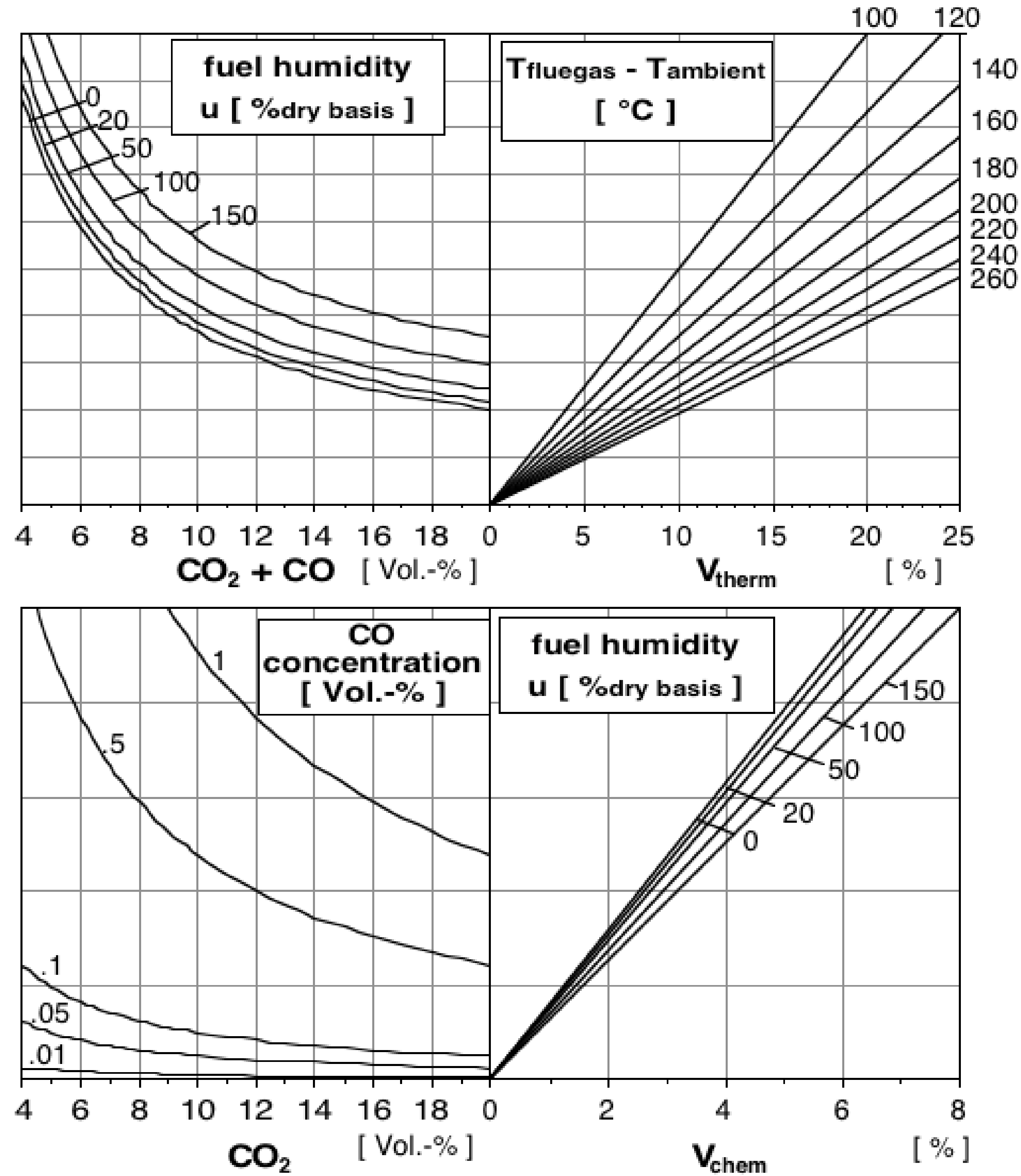

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