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Determination of Lower Heating Value of Municipal Solid Waste by Mathematical Analysis of a Plant Production Data from a Real Waste-to-Energy Plant

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Lower heating value represents a key parameter influencing performance and economy of any combustion process. This article presents a methodology for determination of LHV of municipal solid waste (LHV_W) by processing set of operational data from a real waste-to-energy plant. In the introductory part the LHV_W is evaluated according to the procedures recommended by the Reference document on the Best Available Techniques for Waste Incineration (BREF/BAT). We discuss suitability of using the general regression-based equation for a specific plant with different technological solution of the particular subsystems.
The acquired LHV_W also served as an initial estimate for subsequent calculation of combustion chamber efficiency. There is strong relationship between the LHV_W and boiler efficiency. The efficiency was calculated by three different methods: the direct, the indirect and the "modified" indirect method. The first two methods are commonly used in practice. Third method has been developed by the authors as a control mechanism and complementary approach to the first two. Because different input parameters are needed for each method, it is the purpose of this contribution to show difference in obtained results. Each method is variously sensitive to a change in input parameters and this was utilized to make values of input parameters more precise (especially the low heating value) and to estimate possible inaccuracy in their determination. For this purpose a computational tool has been developed and is introduced in the paper.

1. Introduction

The highest requirements in terms of securing minimal impact on the environment and achieving maximized efficiency are placed on Waste-to-Energy plants (WtE). An overview is offered by the European Commission document BREF/BAT (European IPPC Bureau, 2006). Two of the many measures recognized as a best practice are LHV_W and the boiler efficiency (η_B) evaluation. These parameters are closely interconnected. The efficiency is determined from the LHV_W and the other way around. It is important to know both these parameters for efficient process control and for drawing up production plans. Thus, these parameters have a great impact on the operation economics.
The LHV_W represents also important input parameter for many calculations, e.g. for determining the amount of electricity produced from highly-efficient cogeneration (Directive 2004/8/EC), the amount of electricity produced from secondary energy sources, etc. (Fellner, 2007). The knowledge of the LHV and η_B can also be used to evaluate the R1 (Energy efficiency) (Grosso, 2010; Reiman, 2006), which categorizes the plant as disposal or recovery (Directive 2008/98/ES, 2008).

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2. Computation of Lower Heating Value from Production Data

Determining the LHV_W is quite problematic (Chang, 2007; Chang, 2008). Because of its non-homogeneity and variable composition, it is almost impossible to take a representative sample (European IPPC Bureau, 2006). That is the reason why, in practice, the LHV_W is evaluated indirectly using on-line measured operational data. The following regression equation is recommended (Reimann, 2003) .

$$LHV_{W,R} = 1.133 \cdot \frac{\dot{m}_{ST,W}}{\dot{m}_W} \cdot i_{ST,HP,NET} + 0.008 \cdot t_{SP4} - 0.801 \quad (1)$$

Where:
$LHV_{W,R}$ - Lower heating value of waste according to Reimann [GJ/t] (REIMANN)
$\dot{m}_{ST,W}$ - The amount of steam produced from waste without steam produced from imported energy [t/r]
$\dot{m}_W$ - The amount of processed waste [t/r]; t_{SP4} - The temperature of flue-gas at the boiler output [°C]
$i_{ST,HP,NET}$ - Enthalpy increase in the boiler [GJ/t]; 0.008 - Specific energy floe in flue-gas at 4 – 12 % O_2 concentration [GJ/t*°C]; 1.133, 0.801 - coefficients of the regression equation.

Equation (1) was obtained by comprehensive analysis of operational data from a large number of plants operated in different EU countries. If applied on specific WtE, this regression cannot take into account specific features related to particular technology lay-out. Eq. 1 has to be adjusted according to local conditions (steam taken from the boiler at several parameters, air preheating system design, the existence of flue-gas recirculation, etc.).

Thus, to evaluate the LHV_W in a particular case, it is necessary to know internal energy flows within the plant and to set correctly the borders of the evaluated system. All the additional and circulating energy flows contribute to steam production. Therefore for correct evaluation of the LHV_W or η_B they have to be subtracted.

This correction was carried out for an existing plant., As a part of internal energy management, the primary air is preheated in two stages with saturated steam taken from the boiler drum and low-pressure steam from turbine. Further a part of the flue-gas taken from the main flow behind the electrostatic precipitator (ESP) is introduced back into the combustion chamber as so called tertiary air. The comparison of the LHV_W gained this way (hereafter referred to as corrected) considering these energy flows with the uncorrected LHV according to the general Eq. 1 is depicted in the Figure 1.

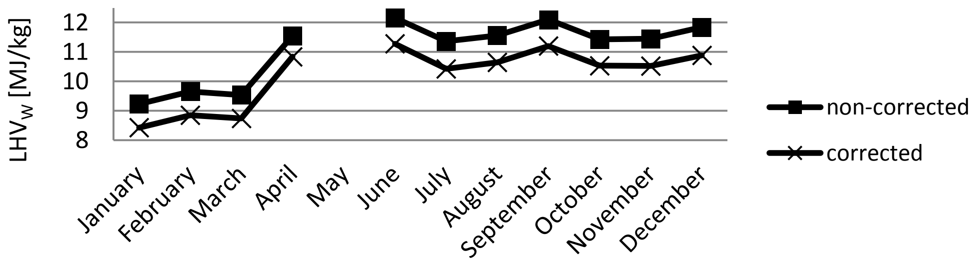


Figure 1: Comparison of LHVW,R with a correction including air preheating and flue-gas recycling

The graph shows an evident difference in the LHV_W (almost 1 GJ/t waste). Considering the validity of original relations, an omission would lead to a 7 % error in the LHV determination.

3. Calculation of Boiler Efficiency

Generally, the η_B represent relation between effectively utilized heat (Q_{prod}), heat losses (Q_{loss}) and heat introduced into the boiler (E_W). Direct and the indirect method are widely used for evaluation combustion system efficiency.

3.1 Direct Method

Using the direct method is in general suitable for systems incinerating homogeneous fuel. If such an approach is applied on WtE, this can lead to inaccurate results due to expected significant measuring error in input parameters (amount of incinerated waste, the LHV_W and in some cases also steam produced in boiler (FDBR, 2000)). The overview of all parameters entering the computation for the direct method is present in the Table 1.

Table 1: Input parameters for direct method

Input parameter	Unit	Measurement
Amount of incinerated waste	t/h	Weighing at crane weigher (actual value) Long term correction based on lorry weigher
Lower heating value (LHV_W)	GJ/t	Backward computation (Eq. 1)
Flow rate(s) of steam produced in a boiler (steam for steam turbine, technological steam, etc.)	t/h	Flowmeter
Steam enthalpy	GJ/t	Computation from measured temperatures and pressures
Feed water flowrate	t/h	Flowmeter
Feed water enthalpy	GJ/t	Computation from measured temperatures and pressures
Blowdown flow	t/h	Flowmeter or computation or possibly a qualified estimate
Blowdown enthalpy	t/h	Computation

3.2 Indirect Method

The indirect method eliminates the problem with determining the fuel rate. Unlike the direct method, only one parameter here is possibly burdened with a significant error – the LHV_W. The indirect method principle lies in subtraction of particular boiler losses (EN 12952, 2003).

$$\eta_{B,IN} = 100 - (\xi_{MN} + \xi_{CN} + \xi_f + \xi_k + \xi_{SV}) \tag{2}$$

where, ζ_{MN} - losses due to unburned combustibles in grate and fly ash [%], ζ_{CN} - losses due to incomplete combustion [%], ζ_f - losses due to enthalpy in grate and fly ash [%], ζ_k - flue gas losses [%], ζ_{SV} - losses due to radiation, conduction and convection [%]

The parameters entering the computation with indirect method are summarized in the Table 2.

Table 2: Input parameters for the indirect method

Input parameter	Unit	Measurement
Boiler thermal output	MW	Computation from flow of produced steam and its parameters (for needed parameters see the direct method)
Lower heating value (LHV_W)	GJ/t	Backward computation Eq. (1)
Waste composition	% mass	estimate, balance data
O_2 conc. in flue-gas at boiler outlet	% vol.	Measured
Amount of flue-gas at boiler outlet	m_N^3/h	Measured or balance data
CO conc. in flue-gas at boiler outlet	% vol.	Measured at the stack

3.3 "Modified" Indirect Method

The third method called the "modified" indirect method was developed by the authors as a control procedure for the first two well-established methods. The "modified" indirect method is based on an adjustment of the basic balance equations for direct method and Eq. (2) to the following form:

$$\frac{1}{\eta_{B,MIN}} = \frac{1}{\dfrac{Q_{prod}}{Q_{prod} + Q_{loss}}} = \frac{Q_{prod} + Q_{loss}}{Q_{prod}} = 1 + \frac{Q_{loss}}{Q_{prod}} = 1 + \left(\xi_{MN} + \xi_{CN} + \xi_{f} + \xi_{k} + \xi_{SV}\right) \tag{3}$$

Where: $\eta_{B,N}$ - modified losses due to unburned combustibles in grate and fly ash [%], ζ_{MN} - modified losses due to incomplete combustion [%], ζ_{f} - modified losses due to enthalpy in grate and fly ash [%], ζ_{k} - modified flue gas losses [%], ζ_{SV} - modified losses due to radiation, conduction and convection [%]. This procedure is not accepted in practice and its importance cannot be easily imaginable as in case of the previous two methods. Certain adjustment of particular losses calculations (ζ_{MN}, ζ_{f} , ζ_{k}...) used in indirect method is necessary. Without providing any details, it is stated that unit heat produced ($Q_{prod}/\dot{m}_{w}$) enters the calculation instead of LHV_W. This way, it was possible to exclude the LHV_W completely from the calculation.

3.4 Boiler Efficiency of an existing WtE plant

In case of an "ideal" system, we can assume that the results given by the direct, the indirect or the "modified" indirect method are the same. In a real system, where the input parameters can be burdened with measurement error, this does not have to be true. From the difference in results, a systematic error in measurement of one of the crucial parameters can be deduced.In the following text, we continue with evaluating of operational data from the given technology whose LHV was determined in Section 2. Average values of LHV_W in particular weeks of the year for all of the three methods are depicted in the Figure 2. Significant differences between methods can be observed.

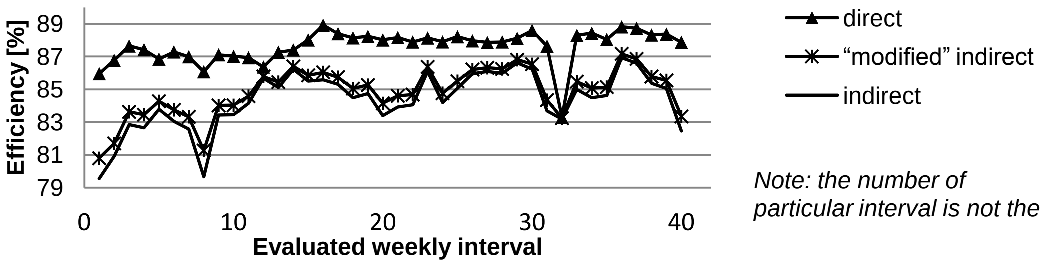


Figure 2: Weekly efficiency of the boiler for direct, indirect and "modified" indirect method

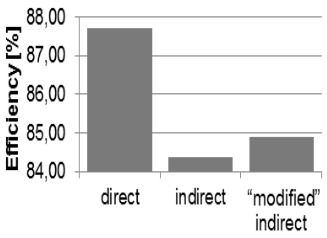
4. Input data validation for increased calculation accuracy

The accuracy of the efficiency calculation is determined by the precision of the input data entering each method (see Table 3). Influence of input parameters correction on η_B calculated by these tree methods was tested. The general goal is to minimize differences in resulting values.

Table 3: Main parameters influencing resulting values of efficiency

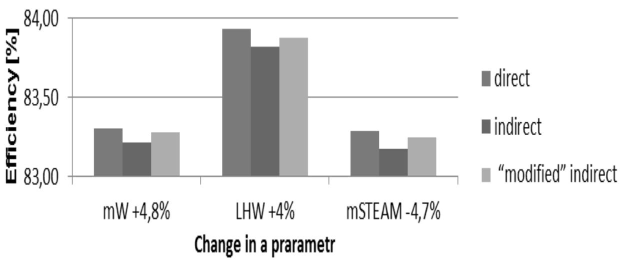
Direct method	Indirect method	"Modified" indirect method
LHV	LHV	Amount of incinerated waste
Amount of incinerated waste	Amount of produced steam	Amount of produced steam
Amount of produced steam	Temperature of flue-gas at the output from boiler	Temperature of flue-gas behind the boiler
	Oxygen levels in flue-gas	Oxygen levels in flue-gas

Because of the attempt to keep this paper clear, we present the procedure only for one evaluated week, where the η_B was close to the average value for an entire year. The previously obtained values for this period are shown in the Figure 3.
The computation of the efficiency in this period of time was repeated several times, and every time one of the parameters from the Table 4 was corrected to simulate inaccuracy of measurement. Other input parameters were fixed as we strived to evaluate the influence of the change.
As expected, it was confirmed that the greatest influence on the resulting η_B have the amount of incinerated waste, it's heating value and the amount of produced steam. Their influence can be seen in the Figure 4. In comparison with the obtained results (Figure 3) it can be stated that the η_B in given time period was determined more precisely. The value of the efficiency varied between 83 and 84 %.



a) before correction

Figure 3: Values of η_B in the week 32



b) after correction

Figure 4: Correspondence of η_B computed by particular methods with altered principal parameters

The obtained data can also be processed in the statistical software (see Figure 5). Although the η_B computed with different methods have close arithmetical means and medians, they vary in the shape of the histogram (LEHMANN, 1998). In an ideal system the data should vary only because of random errors. So we do not reject the hypothesis about obtaining data from the same distribution, i.e. the shapes of the histograms and standard errors would also be close. But this cannot be achieved in one observed interval.
The presented approach serves for a systematic analysis of operational data from WtE plants in order to refine the LHV_W and η_B in a long time period. The described methodology in combination with detailed statistical result processing creates a potential for revealing in accuracies and systematic errors in measurement and final calculation of important production indicators.

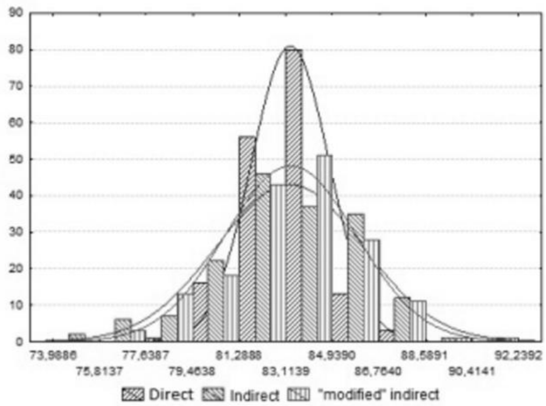


Figure 5: Histogram of η_B with a + 4.8 % change in amount of incinerated waste

5. Conclusion

This paper addresses processing of operational data from an up-to-date WtE plant. In the introductory part the analysis of LHV_W was carried out in accordance with methodology recommended in the

BREF/BAT document. The necessity for correction taking into account specific features in technology design was stressed. In presented case study the LHV_W varied during the year between 8.4 GJ/t to 11.3 GJ/t. The LHV_W further served as an input parameter for computing boiler efficiency.The calculation was performed using the direct, the indirect and the “modified” indirect methods. Because the particular methods require different input parameters, the objective of the computation was to show the differences in the results and point out the possible measurement errors. The assumption was made that in an ideal balance system equal results should be reached. The procedure was presented on a specific time-interval . The computation confirmed that the main parameters influencing the resulting value of efficiency are the LHV_W, amount of waste incinerated and the amount of produced steam.The inaccuracy in measurement was quantified and boiler efficiency 83 to 84 % was obtained.

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