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Improving Calculation of Lower Heating Value of Waste by Data Reconciliation – Analysis and Evaluation

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Lower heating value represents a key parameter influencing performance and economy of any combustion process including waste incineration. Lower heating value of waste (LHVW) evaluation is a challenging task due to the heterogeneity of this specific type of fuel. In the long term (annually, monthly), LHVW may be evaluated according to the regression function recommended by the Reference document on the Best Available Techniques for Waste Incineration (BREF/BAT). Special attention has to be paid to specific features related to particular technology. The acquired LHVW also serves as an initial estimate for subsequent calculation of combustion chamber efficiency.
This paper extends previous work on the topic of LHVW evaluation and analyses the possibility of simultaneous LHVW and also efficiency evaluation improvement by applying data reconciliation principle. This method could generate more precise data used as input parameters for subsequent plant operation planning on a short term basis. The idea consists in the fact that the efficiency calculations by different available methods should be equal. The equality may be achieved by modifying values of significant parameters (waste input, LHVW, steam output) simultaneously. But the modified values should be close to original values to have meaningful results. This procedure leads to nonlinear optimization problem. The potential of the approach is evaluated on the basis of a comprehensive analysis.

1. Introduction

Lower heating value of waste (LHVW) represents a key parameter for designing a Waste-to-Energy (WtE) plant. Therefore, good estimation of LHVW value and variability during a year as well as its change in future are very important. Design based on wrong estimation may lead to significant operational problems. Moreover, LHVW significantly influences economics of a WtE project. An estimation of LHVW is very problematic regarding heterogeneous nature of waste. A research in this field could help to design new plants more efficiently and consequently to avoid operational problems.
Generally, lower heating value can be evaluated by several approaches:

- Evaluation based on known composition (composition analysis → higher heating value → lower heating value),
- Evaluation based on known fraction composition and estimation of fraction heating value,
- Backward calculation using operational data.

The first two methods are acceptable for homogenous materials (coal, wood, etc.). However, composition of waste is very uncertain. The backward calculation is used in case of existing WtE plant. The effort of the authors is to provide the best possible estimation of LHVW. The estimation approach assumes utilization of available data related to LHVW (analyses dealing with fractional composition and production of waste in different areas and operational data analyses) and application of advanced mathematical methods.
Combining knowledge of waste collecting area, outputs of experimental research, social-economic data and data from existing plants, authors expect development of a model giving good estimation of LHVW. Important step in this process is detailed and clearly defined processing of available operational data from existing WtE plants. This step is the subject of the presented paper. In particular, the paper deals with the improvement of backward calculation of LHVW and follows the work by Benáčková et al. (2012), where the

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idea of improvement was suggested. The improvement is based on data reconciliation method (Narasimhan and Jordache, 1999). The idea is further developed and results are discussed.

2. Lower heating value of waste calculation and steam boiler efficiency

The heating value calculation represents a difficult problem. Van Kessel et al. (2004) described online LHVW calculation based on mass balance. Horeni and Beckmann (2006) introduced an online balancing program for WtE plants providing calculation of LHVW using balance method which is able to calculate many important parameters. Fellner et al. (2007) described a balance method which calculates LHVW using measured data. All these approaches represent useful and easy-to-apply tool, however, more or less there may be some obstacles such as missing measurements or variation in chemical composition of waste. The formula presented in The Reference document on the Best Available Techniques for Waste Incineration (European Commission, 2006) and the formula presented by Reimann (2006) may be also used for backward LHVW calculation using online measured data. These formulas were obtained by analysis of operational data from large number of plants.

The method presented in this paper uses these formulas for LHVW calculation. The formulas provide good estimation of LHVW but they cannot reflect specific features related to particular technology such as steam taken from the boiler at several parameters, air preheating system design, the existence of flue-gas recirculation, etc. (Benáčková et al., 2012).

LHVW is one of the essential parameters of boiler efficiency calculation. The efficiency is determined from the LHVW and the other way around. There are two methods widely used for efficiency calculation – direct and indirect (FDBR, 2000). The method called the “modified” indirect method was developed by the authors as a control procedure for the first two well-established methods - details on modified indirect method were presented by Benáčková et al. (2012)). Each method has different inputs which are summarized in Table 1.

Table 1: Inputs for boiler efficiency calculation

Direct method	Indirect method	“Modified” indirect method
Lower heating value	Lower heating value	Amount of incinerated waste
Amount of incinerated waste	Flow rate(s) of produced steam	Flow rate(s) of produced steam
Flow rate(s) of produced steam	Flue-gas temperature at the boiler outlet	Flue-gas temperature at the boiler outlet
Steam enthalpy	Amount of flue-gas at the boiler outlet	Amount of flue-gas at boiler outlet
Feed water flowrate	CO conc. in flue-gas at the boiler outlet	CO conc. in flue-gas at a boiler outlet
Feed water enthalpy	Waste composition	Waste composition
Blowdown flow	O_2 conc. in flue-gas at the boiler outlet	O_2 conc. in flue-gas at boiler outlet
Blowdown enthalpy		

Theoretically, efficiencies calculated by these three methods should be equal. However, the input parameters are affected by error and the efficiencies differ. This is demonstrated on efficiencies calculated using operational data from existing WtE plant (Figure 1). The difference between efficiencies is used in presented approach to identify errors.

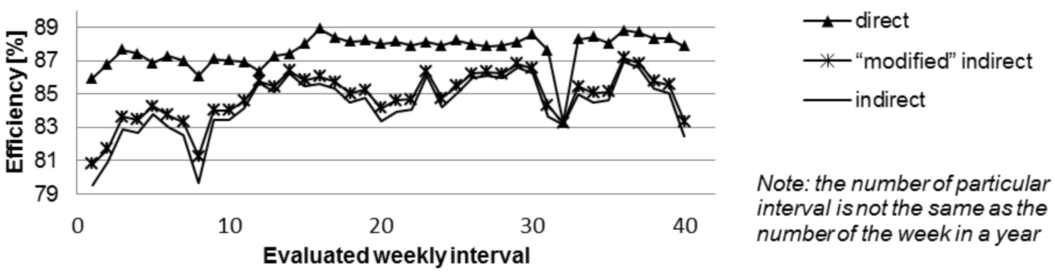

Figure 1: Weekly efficiency of the boiler in existing WtE plant for direct, indirect and “modified” indirect method (Benáčková et al., 2012)

3. Improvement in calculation of waste lower heating value

There are two types of error in measurement – random and systematic. Random error is caused by unpredictable influences. It is normally distributed random variable with null mean value. Systematic error occurs due to imperfect calibration or due to wrong data handling system, for example. Measurements affected by systematic error have mean value significantly different from the actual value.
Most of the inputs from Table 1 are assumed to be not affected by error in further work. Error (random and/or systematic) is assumed only in case of:

- Lower heating value,
- Amount of incinerated waste,
- Flow rate of produced steam.

3.1 Improving approach

The improvement consists in identification of errors (systematic errors primarily) affecting the considered parameters. The approach applies the idea of data reconciliation technique. Briefly, data reconciliation technique consists in correction of measurements to meet the balance equations describing the process and the correction should be minimal. Therefore it is optimization problem. In our case, the corrected parameters are LHVW, amount of incinerated waste and flow rate of produced steam. The requirement to meeting balance equations is replaced by requirement to equal efficiencies (calculated by direct, indirect and "modified" indirect method). The objective function to be minimized is:

$$a \cdot \left(lhv^{+} - lhv^{0} \right)^{2} + b \cdot \left(\dot{m}_{W}^{+} - \dot{m}_{W}^{0} \right)^{2} + c \cdot \left(\dot{m}_{ST,W}^{+} - \dot{m}_{ST,W}^{0} \right)^{2} \tag{1}$$

where $lhv^{+}, \dot{m}_{W}^{+}, \dot{m}_{ST,W}^{+}$ are measured/calculated values and $lhv^{0}, \dot{m}_{W}^{0}, \dot{m}_{ST,W}^{0}$ are corrected values of LHVW, amount of incinerated waste and flow rate of produced steam. Coefficients a, b, c are weights reflecting how large the error of each parameter is (larger error needs smaller weight). In fact, it is analogue with weighted least square method. The objective function is minimized with respect to:

$$\begin{aligned} \left(\eta_{B,D}^{0} - \eta_{B,I}^{0} \right)^{2} &\le p^{2} \\ \left(\eta_{B,D}^{0} - \eta_{B,M}^{0} \right)^{2} &\le p^{2} \\ \left(\eta_{B,I}^{0} - \eta_{B,M}^{0} \right)^{2} &\le p^{2} \end{aligned} \tag{2}$$

where $\eta_{B,D}^{0}, \eta_{B,I}^{0}, \eta_{B,M}^{0}$ are efficiencies calculated by direct, indirect and "modified" indirect method, respectively, and $\eta_{B,\square}^{0} = f\left(lhv^{0}, \dot{m}_{W}^{0}, \dot{m}_{ST,W}^{0} \right)$. Parameter p represents maximum difference between efficiencies. Ideally, p should be zero. But such a requirement leads to problematic convergence. Therefore some difference is acceptable and $p > 0$. The value of $p = 0.35$ was chosen (maximum difference in efficiencies can be 0.35 %).
Described approach was validated on a testing data. Using the simulation software, a reference values were obtained. These reference values were assumed to be not affected by error. Then random errors and/or random errors in combination with systematic errors were simulated and used to affect the reference values. We obtained the testing data. The improving approach was then applied to the testing data and the results were analyzed by comparison with the reference values.

3.2 Testing and results analysis

Testing data sample with 500 values was used in the validation. Reference values are summarized in Table 2. First of all, sensitivity of efficiencies to errors in considered input parameters was performed. The sensitivity is demonstrated on regression coefficients of functions describing change in efficiencies due to error in parameters. The value of regression coefficient (Table 2) determines how sensitive the efficiency to error. We can see that errors in *lhv* and $\dot{m}_W$ have generally higher impact then $\dot{m}_{ST,W}$. For $\dot{m}_{ST,W}$, we could therefore expect smaller correction by the improving approach. Another interesting result is that indirect method is more sensitive than direct and "modified" indirect method. Therefore, direct method seems to be a driving force of corrections.
The first test was focused on corrections of random error. We simulated random errors corresponding to maximum error of ±3 %. The results of corrections are shown in Figure 2.

Table 2: Regression coefficients representing sensitivity of efficiency calculation methods

parameter	direct method	indirect method	"modified" indirect method
lhv	-0.0837	0.0122	-0.0006
$\dot{m}_W$	-0.0752	0.0000	-0.0098
$\dot{m}_{ST,W}$	0.0226	0.0002	0.0030

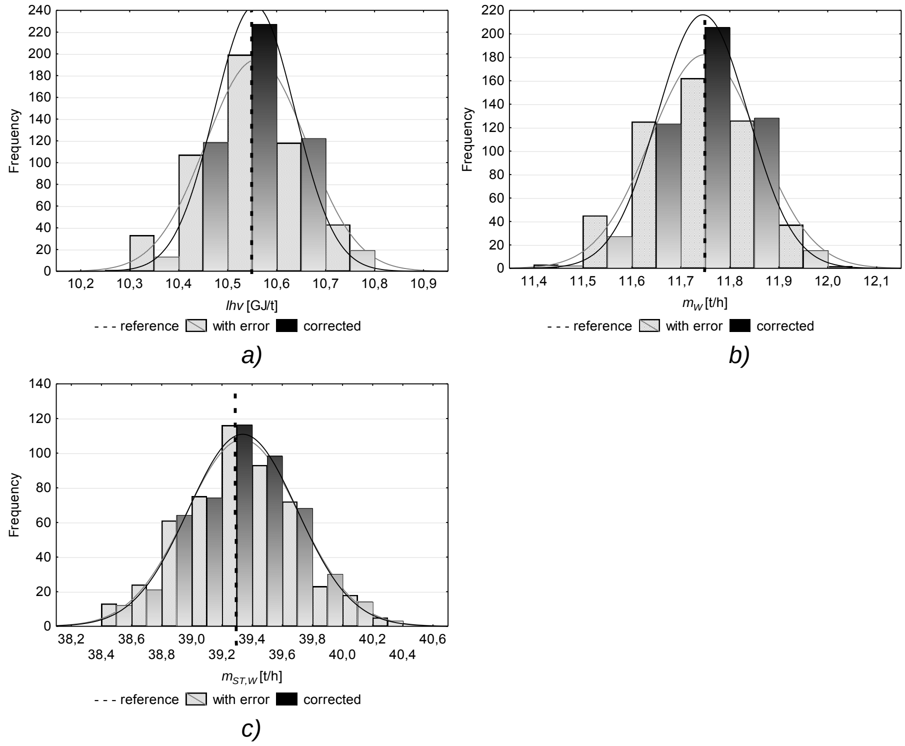

Figure 2: Correction of random errors – a) lower heating value, b) amount of incinerated waste, c) flow rate of produced steam.

The correction of such a small error is not significant. There is very small improvement in case of *lhv* and $\dot{m}_W$ (see deviation in histograms) but almost no improvement in case of $\dot{m}_{ST,W}$. The reason is probably that the error is too small so the constrains are met with very small corrections. Moreover one can also see that the result correspond to results from sensitivity analysis – smaller corrections in case of $\dot{m}_{ST,W}$.
Further we assumed the same random error and added systematic error. The values of systematic error are summarized in Table 3.

Table 3: Values of systematic error

parameter	*lhv*	$\dot{m}_W$	$\dot{m}_{ST,W}$
systematic error	10 %	5 %	0 %

The results were more interesting (see Figure 2). The improving approach proved to identify systematic errors relatively well. One can see that means of corrected values are close to references.
Further we tested the influence of weights. Good choice of weights showed very promising results (Figure 3). The means of corrected values are almost equal to reference values. On the other hand, wrongly chosen weights resulted in very bad corrections. Comparison of results is provided in Table 4. The first choice of weights is rather illogical regarding size of systematic errors. It shows the impact of wrong weights. The second choice corresponds to size of systematic errors and one can see that the correction is much better. The last combination gave the best results (presented in Figure 3). Note that with the corrected data we also get corrected efficiencies.

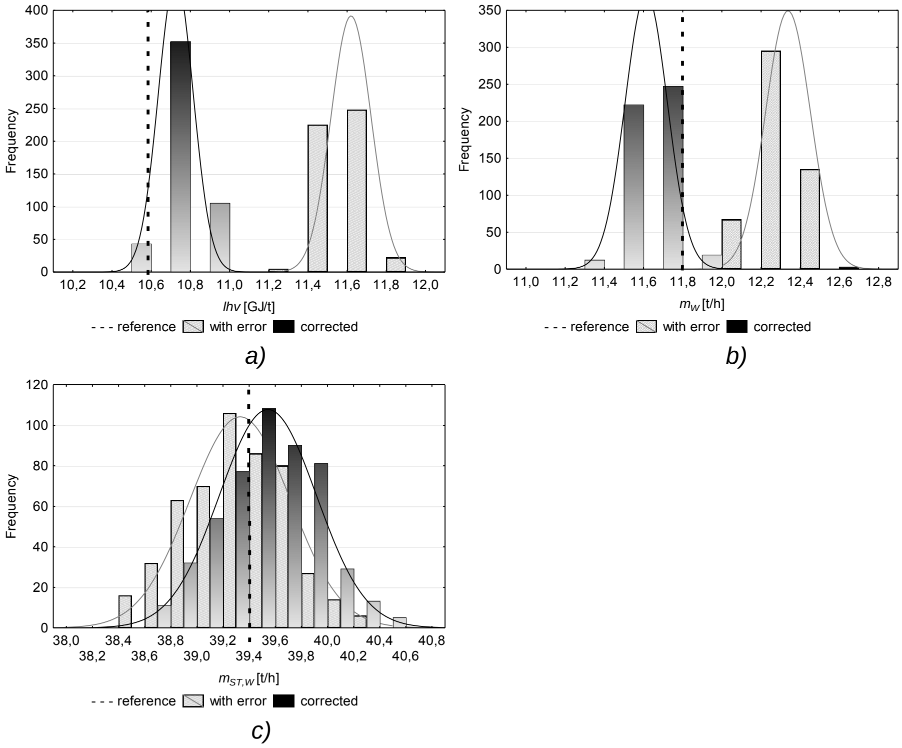

Figure 3: Correction of random and systematic errors – a) lower heating value, b) amount of incinerated waste, c) flow rate of produced steam.

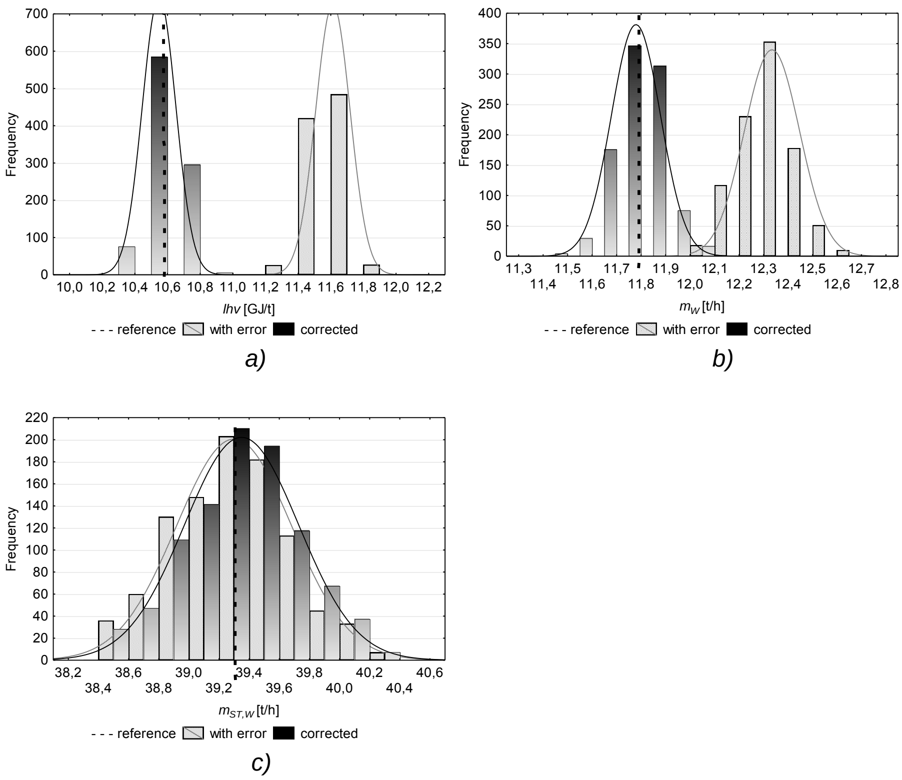

Figure 3: Correction of random and systematic errors using weights – a) lower heating value, b) amount of incinerated waste, c) flow rate of produced steam.

Table 4: Results obtained using different weights

parameter	weight	reference value	mean of corrected values
lhv	0.6	10.55 GJ/t	11.13 GJ/t
$\dot{m}_W$	0.2	11.75 t/h	11.08 t/h
$\dot{m}_{ST,W}$	1	39.32 t/h	39.37 t/h
lhv	0.2	10.55 GJ/t	10.36 GJ/t
$\dot{m}_W$	0.6	11.75 t/h	12.02 t/h
$\dot{m}_{ST,W}$	1	39.32 t/h	39.35 t/h
lhv	0.2	10.55 GJ/t	10.55 GJ/t
$\dot{m}_W$	0.3	11.75 t/h	11.78 t/h
$\dot{m}_{ST,W}$	1	39.32 t/h	39.35 t/h

4. Conclusion

In comparison to methods presented by van Kessel et al. (2004), Horeni and Beckmann (2006) and Fellner et al. (2007), the method described in this paper does not need extensive flue gas measurement and estimation of waste composition and other parameters. The method uses LHVW calculated by formulas presented in BREF document (European Commission, 2006) and also by Reimann (2006) as a good estimation. We proposed improving approach which seems to be a promising tool for reaching higher precision in these calculations. This technique applies the fact that boiler efficiencies calculated by different methods should be equal, which is not true when using real operational data affected by errors. The improving approach corrects the most important parameters (lower heating value, amount of incinerated waste and flow rate of produced steam) to meet the equality between boiler efficiencies

Our results show that the requirement on total equality, which is common in process data reconciliation, is too strict and therefore some difference is tolerated. We assume that this tolerance of minor difference lead to small random error uncorrected. However, in case of larger systematic error, corrected values were close to reference values. Optimal correction was achieved by application of weights which reflects size of error in calculations. The choice of weights is a challenging issue and is a motivation for the future work.

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