ESTIMATION OF RELIABILITY OF BALANCE ANALYSIS OF BOILER FIRED WITH BIOMASS

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Abstract

The total differential method was used to analyze accuracy of balance calculations of a boiler. The input data having the highest influence on credibility (uncertainty) of the balance calculations were shown. There were also pointed out other possible actions leading for the reduction of uncertainty of the balance calculations of a boiler.

Key words: *boiler, algorithm of calculations, estimation of credibility (uncertainty), total differential method*

INTRODUCTION

During different engineering analyses, incl. balance calculations of dryers, boilers etc., a problem of estimation of unreliability or credibility of results is rising. The problem concerns among others the influence of the developed algorithm of calculations. That problem was analyzed in details for wood chips drum dryers and reported in many earlier studies of the author as well as recapitulated in his monograph (Świgoń 2004). The total differential method was presented and applied for the estimation of uncertainty of the investigations and balance calculations. The present work presents the application of the method for the estimation of uncertainty of balance investigations of a boiler as presented in the study of Świgoń and Pawlak (2010).

METHOD OF UNCERTAINTY ESTIMATIONS OF CALCULATIONS RESULTS

The full estimation of results of calculations is possible if measurements and calculations are supplemented with analysis and estimation of uncertainty of measurements. In order to do that uncertainty (i.e. measurement errors) has to be assessed and next check in which extend the uncertainty influences the calculation procedure and therefore the final result (Taylor 1999). For function of several variables

$$z = f(x_1, x_2, ..., x_k) \qquad \text{(a)}$$

and known values of errors (uncertainties) of determining the variables δx_1, δx_2, ..., δx_k one can calculate the absolute error (δz) of the function. When the uncertainties of determining x_1, x_2, ..., x_k are independent and random than Taylor (1999) suggests following formula

$$\delta z^2 = \left(\frac{\partial z}{\partial x_1}\cdot \delta x_1\right)^2 + \left(\frac{\partial z}{\partial x_2}\cdot \delta x_2\right)^2 + \ldots + \left(\frac{\partial z}{\partial x_k}\cdot \delta x_k\right)^2 \quad \text{(b)}$$

The comparison of individual components of the sum of squares of the absolute error δz let to indicate the value δx_j which is decisive for the final value of the uncertainty of the calculations δz (Świgoń 2004).

Some impediment of the final estimation of uncertainty of calculation is related to the complex structure of the function *z*. In such a case the estimation is usually made in subsequent steps. The analysis should avoid excessive rounding of intermediate results in order to get correct final result. However, Taylor (1999) stated that calculation procedure of uncertainty may lead to overestimated values of the final results in subsequent steps. It is always observed when the same value (independent variable) occurs more than once in the function *z*. An example of the overestimation is given in one of earlier studies on the uncertainty analysis (Świgoń 2002).

The only way to avoid the overestimation of the final value of uncertainty is to make the uncertainty analysis for the complex function in one step only. Therefore, it is better to construct the most compact algorithms although it usually complicates the form of the calculation formula.

CALCULATIONS AND THEIR RESULTS

As it was earlier mentioned the uncertainty analysis was made for the input data from the energy balance of boiler as presented by Świgoń and Pawlak (2010). The algorithm presented in that study, i.e. equations (1) to (24), can not be directly applied in the uncertainty analysis. It is due to the fact that in six cases the algorithm would lead to the overestimation of the uncertainty:

- both values $\dot{B}$ and $\dot{P}$, which are found in formula (12), are defined by equations (8) and (9) and depend on $\dot{B}_p$, $\dot{B}_b$ and $\dot{B}_g$, therefore, uncertainty of the difference $(\dot{B}-\dot{P})$ has to be calculated in one step only

$$(\dot{B}-\dot{P}) = B_p\cdot(1-u_p)+\dot{B}_b\cdot(1-u_b)+\dot{B}_g\cdot(1-u_g)=\Sigma\left[\dot{B}_i\cdot(1-u_i)\right] \quad (25)$$

- values occurring in formula (13) are described with relationships (11) and (12) and they contain joint elements, i.e. $\dot{M}_{wB}$ and $(\dot{B}-\dot{P})$ depend on $\dot{B}_i$, while $\dot{M}_{wp}$ and $\dot{M}_{pw}$ are described with relationships constructed with the same values, therefore the uncertainty analysis should be done with use of the following formula

$$X_s = \frac{\overline{v}_N\cdot(X_{pw}\cdot M_{ps}+M_D)\cdot\Sigma\left[\dot{B}_i\cdot(9\cdot h_i+w_i)\right]+\dot{V}_{Npw}\cdot X_{pw}\cdot M_{ps}\cdot M_D}{\overline{v}_N\cdot(X_{pw}\cdot M_{ps}+M_D)\cdot\Sigma\left[\dot{B}_i\cdot(1-u_i-9\cdot h_i-w_i)\right]+\dot{V}_{Npw}\cdot M_{ps}\cdot M_D} \quad (26)$$

- both values occurring in formula (16) depend on X_{pw}, therefore one has to use the following formula

$$\dot{Q}_{pw} = \frac{\dot{V}_{Npw}\cdot(1+X_{pw})\cdot M_{ps}\cdot M_D}{\overline{v}_N\cdot(X_{pw}\cdot M_{ps}+M_D)}\cdot\left[c_{ps}\cdot t_{pw}+X_{pw}\cdot(r+c_D\cdot t_{pw})\right] \quad (27)$$

- the value $\dot{M}_{sw}$ occurring in equation (21) depends on $\dot{B}_i$ and $\dot{M}_{pw}$, while h_{sw} depends among others on X_s, i.e. also on $\dot{M}_{sw}$, therefore the uncertainty has to be estimated using the following extended equation

$$\dot{Q}_{sw} = \frac{\overline{v}_N \cdot \left(X_{pw} \cdot M_{ps} + M_D\right) \cdot \Sigma\left[\dot{B}_i \cdot (1-u_i)\right] + \dot{V}_{Npw} \cdot \left(1 + X_{pw}\right) \cdot M_{ps} \cdot M_D}{\overline{v}_N \cdot \left(X_{pw} \cdot M_{ps} + M_D\right)} \cdot \left[c_{ps} \cdot t_s + \right.$$
$$\left. + \frac{\overline{v}_N \cdot \left(X_{pw} \cdot M_{ps} + M_D\right) \cdot \Sigma\left[\dot{B}_i \cdot (9 \cdot h_i + w_i)\right] + \dot{V}_{Npw} \cdot X_{pw} \cdot M_{ps} \cdot M_D}{\overline{v}_N \cdot \left(X_{pw} \cdot M_{ps} + M_D\right) \cdot \Sigma\left[\dot{B}_i \cdot (1 - u_i - 9 \cdot h_i + w_i)\right] + \dot{V}_{Npw} \cdot M_{ps} \cdot M_D} \cdot \left(r + c_D \cdot t_s\right)\right] \tag{28}$$

- in equation (22) the first component is $\dot{Q}_{pw}$, while the second component may expanded and used for calculating the uncertainty of the difference occurring in equation (23)

$$\dot{Q}_{pw} - \dot{Q}_{s1} = \frac{\dot{V}_{Npw}}{\overline{v}_N \cdot p_b} \cdot \left[p_b \cdot M_{ps} - \varphi_w \cdot p_{nw} \cdot (M_{ps} \cdot M_D)\right] \cdot$$
$$\cdot \left[c_{ps} \cdot t_{pz} + \frac{R_{ps}}{R_D} \cdot \frac{\varphi_{pz} \cdot p_{nz} \cdot (r + c_D \cdot t_{pz})}{p_b - \varphi_{pz} \cdot p_{nz}}\right] \tag{29}$$

while the formula calculating $\dot{Q}_{s1}$ should be expanded to the following form

$$\dot{Q}_{s1} = \frac{\dot{V}_{Npw}}{\overline{v}_N \cdot p_b} \cdot \left[p_b \cdot M_{ps} - \varphi_w \cdot p_{nw} \cdot (M_{ps} - M_D)\right] \cdot$$
$$\cdot \left[c_{ps} \cdot (t_{pw} - t_{pz}) + \frac{R_{ps}}{R_D} \cdot \frac{\varphi_{pw} \cdot p_{nw} \cdot (r + c_D \cdot t_{pw})}{p_b - \varphi_{pw} \cdot p_{nw}} - \frac{R_{ps}}{R_D} \cdot \frac{\varphi_{pz} \cdot p_{nz} \cdot (r + c_D \cdot t_{pz})}{p_b - \varphi_{pz} \cdot p_{nz}}\right] \tag{30}$$

- the highest expansion is related to equation (23) because the formula

$$\dot{Q}_{s2} = \left(\dot{Q}_{pw} - \dot{Q}_{s1}\right) + \Sigma\left[\dot{B}_i \cdot Q_{ii}\right] + \dot{Q}_w - \dot{Q}_D - \left\{\Sigma\left[\dot{B}_i \cdot (1-u_i)\right] + \dot{M}_{pw}\right\} \cdot$$
$$\cdot \left[c_{ps} \cdot t_s + X_s \cdot \left(r + c_D \cdot t_s\right)\right] \tag{31}$$

requires substitutions of $(\dot{Q}_{pw} - \dot{Q}_{s1})$ according to (29), $\dot{M}_{pw}$ according to (5) and X_s according to (26) – due to the limited space of the paper the final form of the formula was not presented here.

The modification of the algorithm of the uncertainty analysis let to skip intermediate equations (2), (3), (4), (6), (8), (9), (10) and (11) in the numerical procedure. It has to emphasized that the presented modification of the algorithm does not change results of the calculations but only enables obtaining the correct value of the uncertainty.

The results of the calculations were rounded according to generally binding rules and the adequate number of significant digits was left (Taylor 1999). The maximum values of the uncertainty of the calculation is given below:

X_{pw}	= (0.0084 ± 0.0013) kg/kg	(± 16.0%)
$\dot{M}_{pw}$	= (17.26 ± 0.25)·10^6 kg/month	(± 1.5%)
$\dot{B}_g$	= (0.02155 ± 0.00007)·10^6 kg/month	(± 0.3%)
$\left(\dot{B} - \dot{P}\right)$	= (2.83 ± 0.14)·10^6 kg/month	(± 4.8%)
$\dot{M}_{sw}$	= (20.09 ± 0.29)·10^6 kg/month	(± 1.5%)
X_s	= (0.128 ± 0.006) kg/kg	(± 4.7%)

h_{sw}	$= (0.581 \pm 0.018)\cdot 10^3$ kJ/kg	(± 3.2%)
$\dot{Q}_w$	$= (3.36 \pm 0.05)\cdot 10^9$ kJ/month	(± 1.3%)
$\dot{Q}_{pw}$	$= (1.18 \pm 0.07)\cdot 10^9$ kJ/month	(± 6.0%)
$\dot{Q}_p$	$= (17.8 \pm 2.0)\cdot 10^9$ kJ/month	(± 11.5%)
$\dot{Q}_b$	$= (22.4 \pm 2.2)\cdot 10^9$ kJ/month	(± 10.0%)
$\dot{Q}_g$	$= (1.162 \pm 0.005)\cdot 10^9$ kJ/month	(± 4.2%)
$\dot{Q}_B$	$= (41.4 \pm 3.0)\cdot 10^9$ kJ/month	(± 7.3%)
$\dot{Q}_{sw}$	$= (11.7 \pm 2.0)\cdot 10^9$ kJ/month	(± 16.9%)
$\dot{Q}_{s1}$	$= (1.00 \pm 0.08)\cdot 10^9$ kJ/month	(± 7.2%)
$\dot{Q}_{s2}$	$= (8.7 \pm 2.8)\cdot 10^9$ kJ/month	(± 3.2%)
η_k	$= (0.59 \pm 0.04)$	(± 7.3%)

DISCUSSION

The highest uncertainty (i.e. 32.0%) was related to calculations of the heat flow rate lost due to incomplete and imperfect combustion $\dot{Q}_{s2}$. The analysis of the calculations performed according to formula (b) for equation (31) shows that the uncertainty consists primary of uncertainties of measurements of net calorific values of biomass (Q_{ib} – in 46.0%) and dust (Q_{ip} – in 12.7%) as well as mass flow rates of combusted dust ($\dot{B}_p$ – in 31.2%) and biomass ($\dot{B}_b$ – in 9.6%). That values (especially $\dot{B}_p$ – in 76.0% and $\dot{Q}_{ib}$ – in 72.2%) also decided on significant uncertainty of calculations of the heat flow rate of combusted dust ($\dot{Q}_p$ – 11.5%) and combusted biomass ($\dot{Q}_b$ – 10.0%). Due to the uncertainty of calculations of $\dot{Q}_B$ (7.3%) it also influences the uncertainty of calculations of the efficiency η_k.

In accordance with the calculations analysis made with formula (b) for equation (28), the calculation uncertainty of the heat flow rate lost with combustion gas at outlet ($\dot{Q}_{sw}$ – 16.9%) depends in 95.8% on the uncertainty of measurements of the volume flow rate of air used for combustion $\dot{V}_{Npw}$. On the other hand the calculation uncertainty of absolute humidity of that air X_{pw} (16.0%) is in 98.0% a result of low accuracy of measurements of air relative humidity φ_w.

The above presented very shorten analysis shows that in order to reduce the uncertainty of the balance calculations of the boiler it is required to increase accuracy of measurements of the following values being input data in the analysis: Q_{ib}, Q_{ip}, $\dot{B}_p$, $\dot{B}_b$, $\dot{V}_{Npw}$ and φ_w. In the case of not finding better accuracy of measurements the other options for reduction of the uncertainty of the balance calculations should be found.

It is often practiced to increase the number of measurements and their joined analysis is made according to rules of mathematical statistics. It allows obtaining more credible results with the same accuracy of the input data. However, sometimes the repetition of measurements in the same conditions is not well-grounded from the technical or economical point of view or even impossible.

It is also possible to find other better algorithm of calculations. It can be made by other selection of measured values. In the analyzed balance of the boiler it can be done by the relatively easy measurement of absolute humidity of combustion gas leaving the boiler installation X_s. Results of such a procedure, as applied for the balance analysis of drum dryers, are presented in already reported monograph (Świgoń 2004). It was shown that it is possible to obtain significant simplification of the calculation algorithm and to increase credibility of the calculations.

CONCLUSIONS

1. The estimation of credibility (uncertainty) of the balance calculations of the boiler may be done the use of the total differential method.
2. The application of the total differential method enables identifying the input data which are responsible for the highest errors (inaccuracies) due to the measurement inaccuracies of the data, i.e. finding the data which have the highest influence on uncertainty of calculations. Due to that method the accuracy of the data determination can increased and the uncertainty of the calculations can be reduced.
3. The analysis of different algorithms with the use of the total differential method enables comparing accuracy and credibility of the algorithms and therefore selecting the most advantageous algorithm.

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