ANALYSIS OF ERRORS OF COAL QUALITY MONITORS

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Abstract: On-line nuclear meters have been in use in the coal industry for many years. They have been utilised for coal quality monitoring, in the control systems for coal blending, or for separating coals in the heavy media separation process. Their operation is based on the scattering or the absorption of incident gamma radiation, and the derived density or ash value is the result of a time-averaged measurement. In this paper, errors of ash monitors have been analysed. These errors appear due to several reasons: measurements are performed on samples which inaccurately represent a whole mass of tested coal, measuring methods are sensitive to variations in chemical composition of ash, size distribution of coal and moisture content. The signal from the radiation detector has to be averaged over a long period of time which results in delay of measuring results.

Keywords: errors of measurements, signal processing, coal quality monitoring, radiometric methods.

1. INTRODUCTION

The aim of on-line radiometric coal quality (ash content) meters is to measure mean value of ash content in a certain volume of coal. The amount of coal mass in which ash content is determined depends on the purpose of the measurement. In a case of price negotiations between the client and the producer it is usually a lorry, one wagon or a whole train. In a case of ah meter application in a control system it will be a mass transported by a conveyor during 1-5 min. The measurement of ash content in a given mass of coal is performed on a sample representing the whole tested mass of coal. In case of conventional, laboratory method it is a sample taken according to standards and in a case of on-line ash meter it is a part of coal which interacted with radiation beam during the certain time of coal transportation. In both cases the coal sample represents the tested mass of coal with certain accuracy described by the standard deviation of difference between ahs contents in a sample and tested mass of coal. The bigger the coal sample the smaller the standard deviation of the sample representativeness (Sowerby&Watt, 1990). Conventional (sample combustion) laboratory methods and instrumental methods have measurement errors due to the influence of different disturbances on the measurement result. Radiometric methods, in addition, have stochastic errors of measurement due to stochastic nature of the detected radiation beam which signal has to be averaged during certain period of time.

2. ERRORS OF RADIOMETRIC METHODS

On-line radiometric methods of ash content measurements are based on exposing a sample to a beam of energy from a suitable source and detecting the resultant emission. The inherent natural radioactivity present in coal (mineral matter) can also be measured. The main on-line techniques for ash determination are shown in Fig.1. The first three methods can determine only the bulk ash content. the fourth allows detailed measurement of elements from which ash content can be calculated (Kirchner, 1991, Kirchner&Maude, 1994). These four techniques are: gamma back scattering, gamma absorption, natural radioactivity of mineral matter in coal and excitation of coal nuclei which produce radiations characteristic of the elements present.

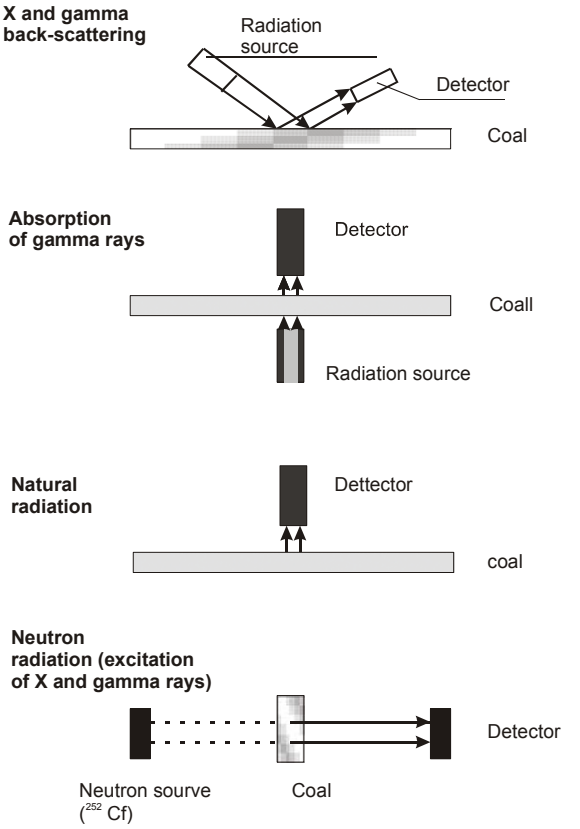

Fig.1. The four main principles for on-line analysis of coal (Kirchner, 1991)

Errors of these measurement methods depend on the applied method itself and mainly on measurement conditions such as: type of coal, size distribution of coal, chemical composition of ash, homogenisation of coal in a cross section of a coal stream, moisture content. Practically experienced errors of the measurement methods are shown in Fig.2.

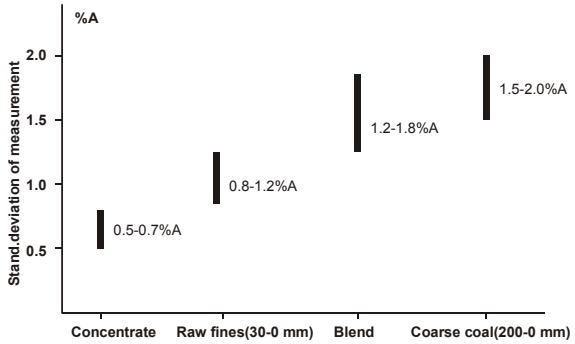

Fig.2. Errors of measuring methods due to variable coal characteristic (size, moisture, chemical composition), %A – percent of ash content.

They depend more on the conditions of measurement (place of installation) than the methods applied (Czerw&Sikora, 1994, Fauth&Bachmann, 1990). The more homogenous and chemically consistent coal is, the better accuracy of measurement can be achieved. The reference method for the above instrumental measurements is always a conventional laboratory method - combustion of a coal sample.

3. ERRORS DUE TO SAMPLE REPRESENTATIVENESS

Ash content measurement in case of a conventional (combustion) laboratory method is performed on samples of coal taken from the main stream of transported material. The samples (number and mass) are taken from the main stream of transported material according to standards (EC). The ash determination is performed by combustion of *analytical sample* which is obtained in the procedure of crushing and dividing from a *general sample* consisting of *primary samples*. Mass of the smallest (according to standards) primary coal samples taken from coals of different size is given in Table 1.

Table 1 The mass of a primary sample as a function of coal size

Maximum size of coal grains, mm	The smallest mass of primary sample, kg
200	12,0
125	7,5
80	4,8
50	3,0
31,5	1,9
20	1,2
10	0,6
1	0,5

The minimum number of primary samples in a general sample is 12 for concentrates and 32 for raw coals. To compare errors of measurements of classical and instrumental methods it is necessary to compare the size of general samples on which measurements are performed.

Standard deviation of the difference of ash content in the sample taken form the large mass of coal and ash content in this coal can be determined from the following equation (Budryk,):

$$U \cdot \sigma^2 = 10^{-6} \cdot c \cdot d_m^3 \cdot \nu^2 \cdot \delta \qquad (1)$$

where: U - sample mass, kg
σ - stand. deviation of ash determination on the basis of a coal sample, %A
c - coefficient of the grains shape,
d_m - mean diameter of coal grains, mm
δ - bulk density of coal, g/cm^3
ν - coefficient of coal non-uniformity,%.

If the coal sample is taken from the coal mass B, then relation between samples having the same standard deviation of ash content determination is given by equation (Budryk, 1948):

$$U_B = \frac{U}{1+\frac{U}{B}} \qquad (2)$$

where: U - mass of a sample taken from the very big mass of coal, kg
U_B -mass of a sample taken from the B mass of coal, kg.

From equations (1) and (2) we obtain the following relation:

$$\sigma = \sqrt{10^{-6} \cdot c \cdot d_m^3 \cdot \nu^2 \cdot \delta \cdot \frac{(B-U_B)}{B \cdot U_B}} \qquad (3)$$

Example: let us determine ash content every 3 hours in raw coal transported on the belt conveyor with the capacity 300 t/h. Let us assume that parameters of the coal are as follows: d_m =30 mm, A = 20%, ν = 25, δ = 0,8 g/cm^3, c = 0,5. For the above parameters the equation (3) is simplified to the following:

$$\sigma = \frac{2{,}6}{\sqrt{U_B}} \text{ , \%A} \qquad (4)$$

Equation (4) is presented in Fig.3.

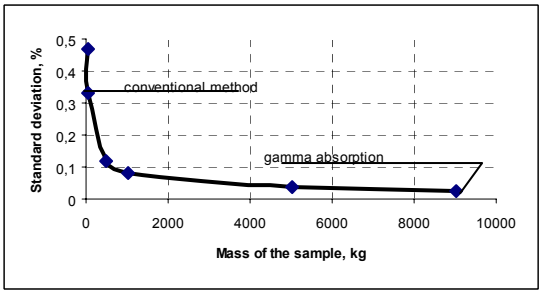

Fig.3. Standard deviation of difference between ash content in a sample and whole mass of tested coal

Mass of a coal sample taken according to Table 1 for conventional method is ca. 61 kg, the mass of coal interacting with nuclear radiation can be estimated to 1-2% (of total transported coal mass) for gamma absorption, 50-60% for gamma backscattering and ca.100% for natural radiation method. Standard deviations of differences between ash contents in samples and in whole mass of coal corresponding to the above mass values are as follows (eq.4):

- conventional (combustion) method: 0,3%A,
- gamma absorption method: 0,027%A
- gamma backscattering: 0,0038%A
- natural radiation: ~0 %A.

Errors of on-line radiometric ash measurements due to sample representativeness are negligible in comparison to such errors in conventional laboratory methods.

4. DYNAMIC ERRORS OF RADIOMETRIC MONITORS

On-line monitors are used at present in three basic applications: monitoring of coal quality, coals sorting (forward control) and in feedback control loops (local systems and overall plant control). The main purpose of monitors application is not necessarily staff reduction but rather making a more consistent product and optimising total production of the plant. The main features of on-line ash monitors as measuring gauges are : accuracy of the indirect measuring method used , response time and general reliability as monitoring and control instrumentation.

The response time of a monitor depends on the average intensity of electric pulses at the output of the radiation detector, which usually is a scintillation counter. The longer the time of measurement, the lower the statistical error of determination of pulses mean intensity. Typical time of measurement, declared by manufacturers of on line monitors, ranges from 1 min to 4-5 min (depends on the method used and parameters of installation). The time of measurement (response time of the instrument) becomes an important parameter in application of monitors in control systems (Cierpisz, 1999).

A general scheme of an on-line ash monitor is shown in Fig.4. Signal processing is similar in all the three measuring methods (back-scattering, absorption, natural radiation). The only difference (from the signal processing point of view) is the mean intensity of output pulses from the detector and the amount of pulses per second corresponding to the 1% of ash content change.

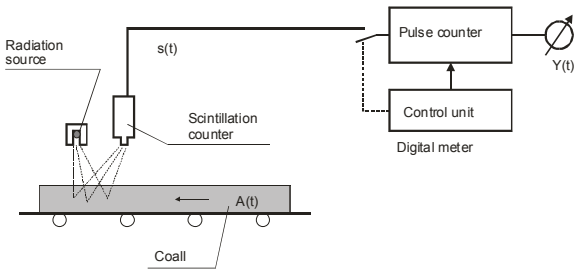

Fig.4. Scheme of the measuring circuit

The series of pulses from the detector (scintillation counter) are counted in a digital counter.
The output signal from the detector is always a stochastic signal, regardless of the character of the input signal (i.e. ash content) modulating the intensity of the detected radiation beam. The response of the ash monitor to the step change of ash content for different times of measurement is shown in Fig.5. The longer the averaging time the higher the statistical (static) accuracy of the monitor.. At the same time, if the input signal varies, the dynamic error of the measurement is higher. This suggests that for a given input signal and a structure of the monitor circuit, one can find an optimal averaging time of input pulses, which gives the minimum dynamic error according to the accepted criteria.

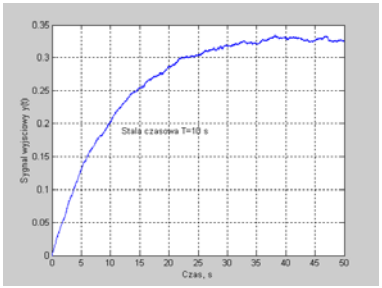

Fig.5a. Run of y(t) dla T=10s

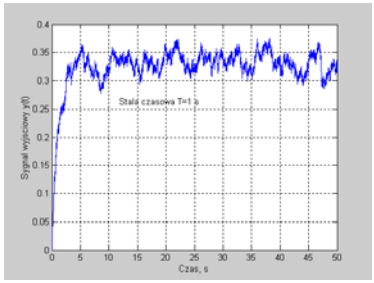

Fig.5b. Run of y(t) dla T=1s

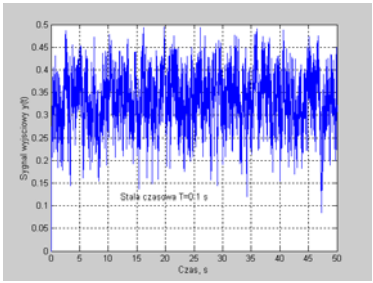

Fig.5c. Run of y(t) dla T=0,1s

A detailed description of the operation of the ash monitor can be found in (Cierpisz,). Let us assume that one wishes to measure accurately a step change of the ash content A(t) controlled by the monitor with the digital counter of pulses shown in Fig.4. That means that the shape of the output signal u(t) should closely resemble the input step function so as to minimise the distance between A(t) and the output signal y(t).

For small changes of ash content $A(t)$ in coal let us assume a linear relation with the mean intensity $n(t)$ of pulses $s(t)$:

$$n(t) = n_o + \Delta n(t) = k_d * (A_o + \Delta A(t)) = k_d * A(t) \qquad (5)$$

The mean intensity of pulses $n(t)$ is determined in the counter with the "moving average", counting at each elementary step T_s (for instance T_s=1 sec) pulses from last "*n-k*" steps. For a given ash content A and corresponding mean intensity of pulses n, the standard deviation of ash measurement s can be approximately determined from the following relation:

$$s = \frac{100}{\sqrt{nT}} * \frac{\Delta n}{\Delta A} \qquad (6)$$

The relation between 2s (doubled standard deviation) and the time of measurement T is shown in Fig.6. The mean intensity of pulses in this example is 10^4 1/s and coefficient $k_d = \Delta n/\Delta A = 100$ 1/s%. The mean intensity of pulses n and coefficient k_d depend on the measuring method, the range of ash measurements, activity of the radiation source and the detector type. For back-scattering and absorption methods their values range from ca. n=(0.5 - 2.0)*10^4 1/s and k_d = (50-300) 1/s% . For natural radiation method n=(150-250) 1/s and k_d=(5-15).

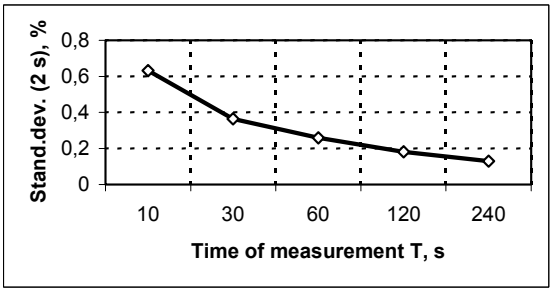

Fig.6. Standard deviation of measurement as a function of the time of measurement

The output stochastic signal $y(t)$ (Figure 4) can be calculated from the equation:

$$y(nT_s) = \sum_{i=n-k}^{i=n} N_i \qquad (7)$$

where N_i is the partial number of pulses which appeared in the i-th elementary interval of time $(i\text{-}1)\cdot_{Tss}...i\cdot T_s$.

The "distance" L_k^2 between the input signal $A(t)$ and the output signal $y(t)$ and the mean value L^2 of L_k^2 are often defined for k-th realisation of the stochastic process as follows:

$$L_k^2 = \int_0^{T_0} [k_d \cdot A(t) - y(t)]^2 \, dt \qquad (8)$$

$$L^2 = \lim_{k\to\infty} \left(\frac{1}{k} \sum_{i=1}^{k} L_i^2\right)$$

In equation (8) T_0 is the time of observation of the signal y(t). The example relation between L and the time of measurement T for a monitor with constant T is shown in Fig.7 (note that the shape of signal y(t) depends on T – Fig.5). The measure of L is defined by ratio L^2/T_0 which unit is expressed in [% of ash]^2.

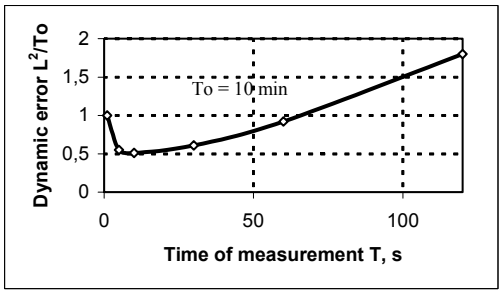

Fig.7. Dynamic error of measurement as a function of the time of measurement

The dynamic error of measurement L is at first big (for short times of measurement), then reaches minimum (for T = 8 s) and then increases due to longer time of measurement. The improvement of dynamics of the system can be achieved introducing the adaptive filter of the signal y(t) in which initial

time of measurement is short and them automatically with time becomes longer (Cierpisz&Heyduk, 2000).

5. SUMMARY

Measuring errors of on-line ash monitors are generated for several reasons. Measurements are performed on a part of whole stream of coal which results in the error due to representativeness of this part. These errors are small and amount from 0 to 0,03%A and are ten times lower than in case of conventional methods for which coal samples are much smaller. The errors of measuring methods due to variable ash chemical composition, size distribution and moisture content are of the order 0,5-0,7%A for uniform concentrates, 0,8-1,2%A for raw fine coals, 1,2-1,8% for blends and ca.2%A for coarse raw coals. Stochastic character of signal from the radiation detector and necessity of its averaging results in dynamic errors of measurement. The dynamic errors depend on the mean intensity of pulses at the detector output, time of averaging of this signal and how rapid are ash content changes. They typically amount from 0,2 to 0,5%A.

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