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On-line monitoring of a coal separation process in a jig – a simulation study

Introduction

At present, simulation models are often used in "soft monitoring systems" to predict the effects of production and to diagnose the technological process and assess whether it meets the required standards over a given period (Cierpisz et al. 2003, 2006). They also, however, show promise in the context of mineral and coal processing plants where information on process performance is typically gained from time and labor consuming laboratory tests on samples of material taken from the feed and products from the beneficiation process.

Generally, coal concentrates from raw coal are produced through gravitational separation processes in heavy media vessels or in jigs (King 2001; Osborne and Fonseca 1992). Both processes are described by similar models of raw coal washability characteristics and a partition curve of the selected machine (shown in Fig. 1).

Raw coal properties are described by the washability characteristics derived from the yield $w(\rho)$ and ash content $a(\rho)$ (or other quality attributes) of elementary density fractions in a given size fraction of raw coal. The effectiveness of a coal separation unit is described by a partition curve which can be used to determine the probability $f(\rho)$ of the elementary fraction flow to the concentrate or refuse. This probability is a function of the density (ρ), the size of the elementary fraction and the separation density of the machine ρ_s. The para-

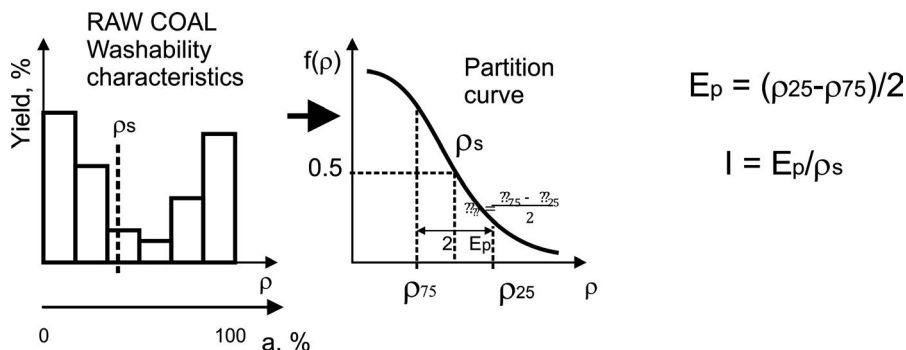* Professor, Institute of Innovative Technologies EMAG, Gliwice, Poland; e-mail: el.st.cierpisz@gmail.com

Fig. 1. A model of raw coal separation in a jig

Rys. 1. Model procesu wzbogacania węgla w osadzarce

meters of the partition curve are "ecole probable" E_p and imperfection I. Raw coal is often beneficiated in three product jigs to obtain concentrate, middlings and refuse as it is shown in Fig. 2.

The tonnage of the raw coal feed to the washing process and its washability characteristics fluctuate with time due to changing underground conditions of coal winning and the changing quality of concentrates. A partition curve describing the performance of a jig also fluctuates with time due to changes in the machine load and size composition of the feed. The quality of the two products (concentrate and refuse) after a washing process depends on the washability characteristics, the partition curve and the separation density, which can be determined only through a periodical laboratory analysis of coal samples taken from the main streams of products. These measurements are time consuming, difficult to perform
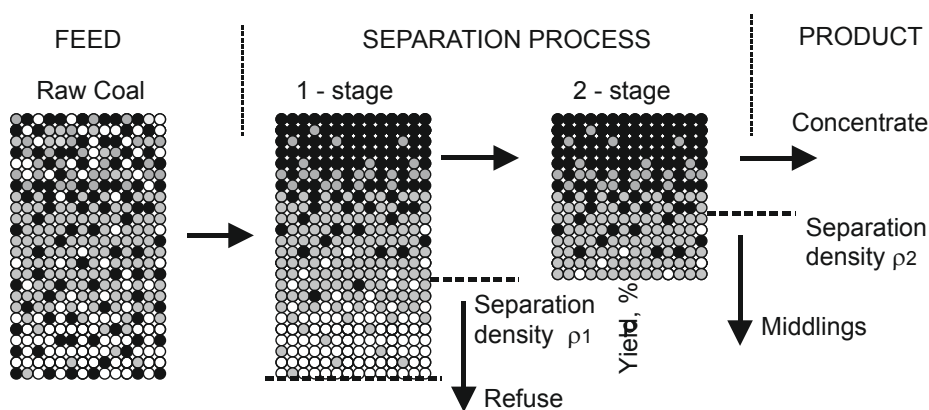

Fig. 2. A three-product coal separation process in a jig

Rys. 2. Trójproduktowy proces wzbogacania węgla w osadzarce

and insufficient for the automatic control of the coal washing processes (Cierpisz et al. 2003; King 2001). Most of the control systems proposed to optimize the economic effect of a technological process requiring the rapid supply of information on raw coal washability characteristics. Some concepts of the on-line identification of the washability characteristics were proposed by Lin et al. (1991, 2000), who used roentgen tomography to monitor the quality and size of each coal particle. Cierpisz (2006) analyzed a soft monitoring system for a coal separation process identification in heavy media vessels and in jigs. In this case, a complex and an expensive system of monitors consisting of belt scales and radiometric ash monitors was proposed. Good results were obtained for the heavy media process. The monitoring of imperfections in jigs did not appear to be satisfactory. In practice, it is still an unsolved problem which results in:

◆ lack of feed-back information for the operators of coal winning machines to change and improve their operation,
◆ lack of information for underground coal stream blending systems to produce a more uniform feed to a coal preparation plant,
◆ operation of coal washing processes at non-optimal separation parameters (densities),
◆ unexpected overcharge of washing machines and other unit operations,
◆ insufficient adjustment of production plans according to variations in raw coal quality.

The aim of this paper is to present an improved method of approximate on-line identification of a partition curve of a jig and washability characteristics of raw coal with the use of a soft monitoring system consisting of three belt scales and two radiometric density meters used for refuse discharge control (Cierpisz et al. 2016; Lyman 1992). This is an important simplification of the system discussed in Cierpisz (2006). The model of the three – product separation process in presented in Fig. 3.
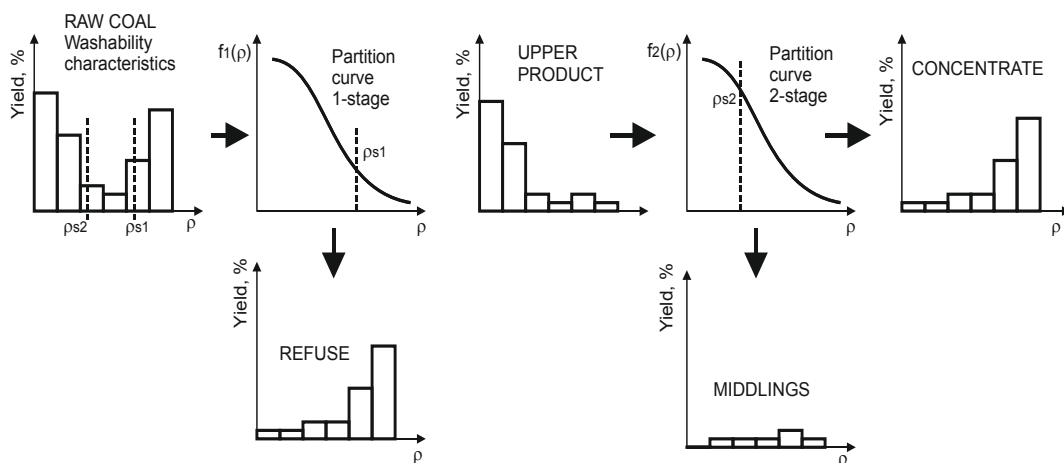

Fig. 3. A model of the three-product coal separation process in a jig

Rys. 3. Model trójproduktowego procesu wzbogacania węgla w osadzarce

In soft monitoring used for on-line identification of the partition curve (imperfection) and the washability characteristics, signals from belt scales (yields of three products) are continuously compared at two different pairs of separation densities in a 3-product gravitational process in a jig with similar signals generated in a simulation model of the process. A set of washability data and partition coefficients is generated in a simulation model with the use of an algorithm (nonlinear, genetic or gradient), and permanently compared with signals from instruments. A block scheme of an idea of the identification system is presented in Fig. 4.
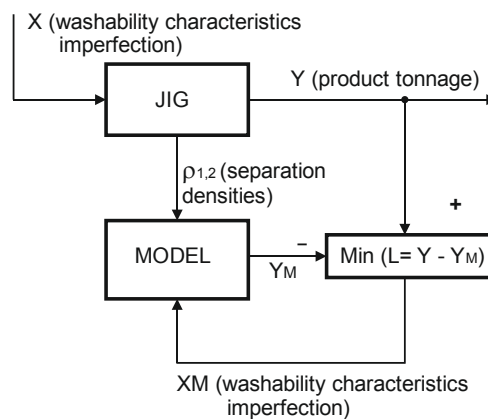
Fig. 4. An idea of a software identification system of coal separation in a jig

Rys. 4. Koncepcja systemu pomiarowego do identyfikacji procesu wzbogacania węgla w osadzarce

1. A model of the process

Raw coal washability characteristics are determined by the yield of elementary fractions w_i in predefined coal density ranges ρ_i and corresponding ash contents in fractions a_i. To simplify the simulation model, the size fractions have been reduced to one and density fractions defined for six constant density ranges $\Delta\rho_i$ (g/cm^3): <1.35; 1.35−1.5; 1.5−1.65; 1.65−1.8; 1.8−1.95; >1.95 (Fig. 5).

Variations of the washability characteristic have been simulated as a stochastic process for all density fractions:

$$w_i(t) = w_{io} + \Delta w_i(t) \tag{1}$$

✑ w_{io} – mean value of the fraction yield;
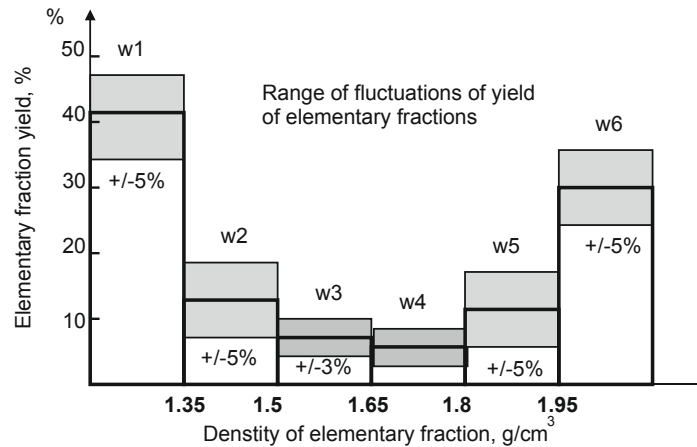$\Delta w_i(t)$ – stochastic process with the mean value equal to zero and with the variance $\sigma^2[w_i]$.

Fig. 5. Variations of the raw coal washability characteristics

Rys. 5. Zmiany charakterystyki wzbogacalności węgla surowego

The partition curve was modeled by the hyperbolic tangent (Zapała 1994):

$$f(\rho_i, \rho_s) = \frac{1}{2} - \frac{1}{2} \cdot tgh\left[\frac{0,5493}{I} \cdot \frac{\rho_i - \rho_s}{\rho_s}\right]$$

$$I = Ep \cdot \rho_s$$

$$Ep = \frac{1}{2} \cdot (\rho_{25} \cdot \rho_{75})$$

(2)

The monitoring system consists of three belt scales and two radiometric density meters measuring the density of the separation layer ρ_w (Cierpisz 2016). The separation density in equation (2) has been calculated on the basis of ρ_w measurements following the logic illustrated in Fig. 6. Fig. 6 shows the stratification of grains in the bed and the process in which the material is separated into the concentrate and refuse.

The following symbols are used in Fig. 6:

- ◆ w_{wi} – yield of the elementary layer of density r_{wi} in the stratified bed, %;
- ◆ a_{wi} – ash content in the elementary layer, %;
- ◆ ρ_{wi} – density of the elementary layer, g/cm^3;
- ◆ q_b – flow rate of the refuse, % of the feed;
- ◆ ρ_{ws} – density of the separation layer, g/cm^3.

The separation layer divides the stratified bed into the upper product (concentrate) and the bottom product (refuse). The yield of the k-th density fraction (ρ_{fl}) in the feed reporting to the concentrate is determined by its partition number f_{ki} in the partition curve for
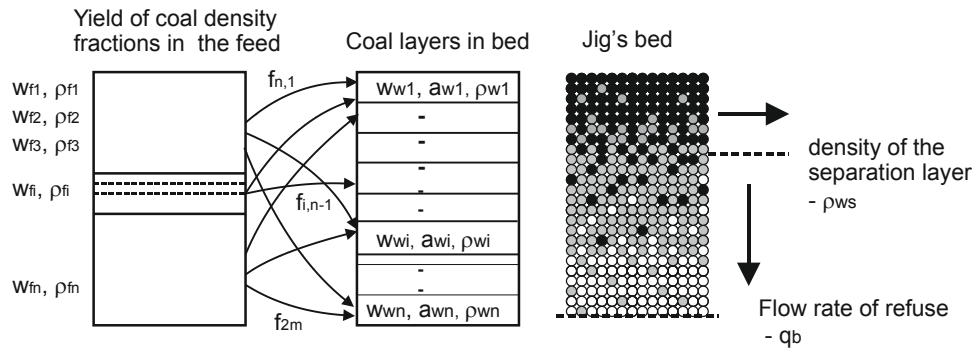
Fig. 6. Coal separation process in a jig – density layers forming

Rys. 6. Formowanie się warstw gęstościowych w łożu osadzarki

the given separation density ρ_{fs}. If we divide the jig's bed to "i" layers of monotonically increasing densities $\rho_{w1}, \rho_{w2}, \ldots, \rho_{wi}$, we can calculate the corresponding yields of density fractions, starting with the first (upper) layer. The flow rate of the first layer consisting of k density fractions (for $h_{\max} = 1$) can be calculated from the equation (4) with normalizing conditions (3):

$$\sum_{i=1}^{i} f_{ik} = 1 \qquad\qquad \sum_{k=1}^{k} w_{fk} = 1 \tag{3}$$

$$w_{f1} \cdot f_{11}\left(\rho_{f1}, \rho_{s1}\right) + w_{f2} \cdot f_{21}\left(\rho_{f2}, \rho_{s1}\right) + \ldots + w_{fk} \cdot f_{k1}\left(\rho_{fk}, \rho_{s1}\right) = \frac{1}{i} \tag{4}$$

The separation density ρ_{s1} can be determined from the equation (10) and then the density ρ_{w1} of the first layer follows from the equation (5):

$$\rho_{w1} = \sum_{k=1}^{k} w_{fk} \cdot f_{k1} \cdot \rho_{fk} \tag{5}$$

For the second layer:

$$\sum_{k=1}^{k} \left[w_{fk} \cdot f_{k2}\left(\rho_{fk}, \rho_{s2}\right) - w_{fk} \cdot f_{k1}\left(\rho_{fk}, \rho_{s1}\right) \right] = \frac{1}{i} \tag{6}$$

For the "i-th" layer:

$$\sum_{k=1}^{k}\left[w_{fk}\cdot f_{ki}\left(\rho_{fk},\rho_{si}\right)-w_{fk}\cdot f_{k(i-1)}\left(\rho_{fk},\rho_{s(i-1)}\right)\right]=\frac{1}{i}$$

(7)

The density of the "i-th" layer:

$$\rho_{wi}=\sum_{k=1}^{k}w_{fk}\cdot f_{ki}\cdot\rho_{fk}$$

(8)

An example of the distribution of three density fractions along the height of the bed in a jig was calculated using equations (3)−(8) for the following data:

- ◆ w_{f1} – yield of the "1" density fraction in the feed (0.5);
- ◆ w_{f2} – yield of the "2" density fraction in the feed (0.2);
- ◆ w_{f3} – yield of the "3" density fraction in the feed (0.3);
- ◆ ρ_{f1} – density of the "1" fraction (1.4 g/cm^3);
- ◆ ρ_{f2} – density of the "2" fraction (1.6 g/cm^3);
- ◆ ρ_{f3} – density of the "3" fraction (1.8 g/cm^3);
- ◆ I – imperfection of the jig ($I = 0.15$);
- ◆ i – number of layers in the bed ($i = 10$).

Fig. 7 shows the distribution of the raw coal density fractions within the layers of the bed, while Fig. 8 shows the relation between the separation density ρ_s and the density of the separation layer ρ_w.
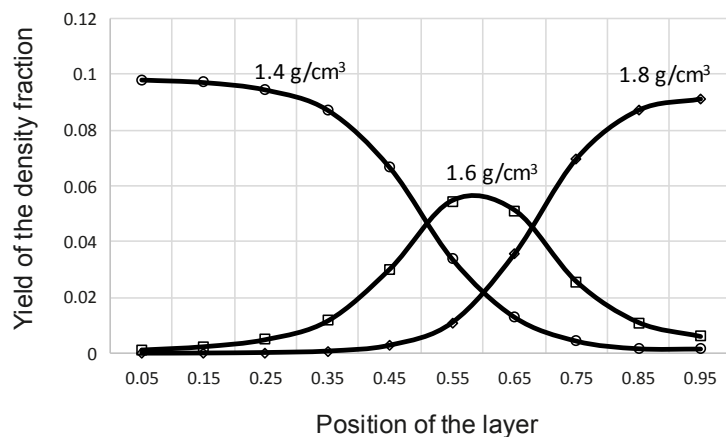

Fig. 7. The distribution of the raw coal density fractions in individual layers of the bed

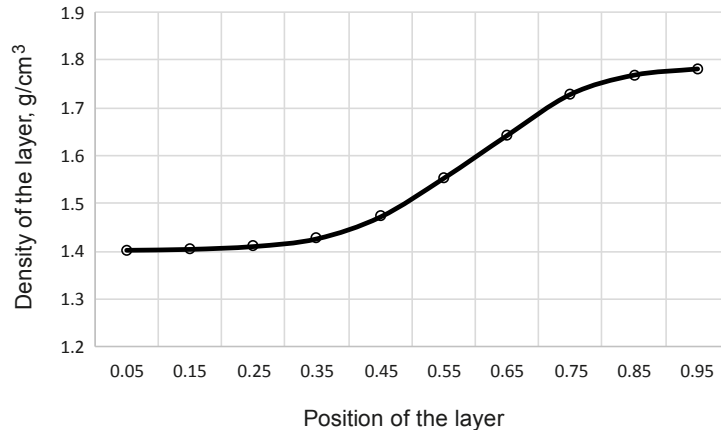Rys. 7. Rozkład frakcji gęstościowych nadawy w łożu osadzarki

Fig. 8. Relation between the separation density and the density of the separation layer

Rys. 8. Zależność pomiędzy gęstością rozdziału i gęstością warstwy rozdziału

2. Simulation analysis

The identification of a coal washing process in a jig is based on a soft monitoring system, in which tonnages of three products are measured at two different pairs of densities of separation layers. Yields of raw coal fractions w_i and imperfection I of the jig are identified on-line. The real washer (three-product jig) and raw coal characteristic have been simulated through equations (9, 10, 11), where tonnages of the three products are given as a function of washability characteristics, partition curve (represented by imperfection I) and two separation densities. The tonnages of all products (Q_c, Q_m, Q_o) are measured by belt scales. The parameters of three products (concentrate, middlings and refuse) can be calculated from the following equations:

◆ Yield Q_c of the concentrate:

$$Q_c = \sum_1^n w_i \cdot f_{i1} \cdot f_{i2} \qquad (9)$$

◆ Yield Q_m of the middlings:

$$Q_m = \sum_1^n w_i \cdot f_{i1} \cdot \left(1 - f_{i2}\right) \qquad (10)$$

◆ Yield Q_o of refuse:

$$Q_o = \sum_1^n w_i \cdot (1 - f_{i1})$$

(11)

↳ f_{i1}, f_{i2} are partition numbers at the first and the second stage of coal washing in the jig.

They create a vector determining the tonnages of products. These six signals (three for the first pair of separation densities and three for the second pair) are compared to the respective six signals ($Q_{cx1,2}$, $Q_{mx1,2}$, $Q_{ox1,2}$) generated in the on-line simulator (Fig. 9) working in parallel with the identified system.

The on-line simulator automatically generates sets of washability characteristics, imperfections and separation densities. The generated values create a vector defining the simulated properties of the three products. The best set of generated values is chosen on the basis of the minimal "distance" between the two vectors according to the criterion shown in equation (12):

$$\text{Min}\{L\} = \text{Min}\left(\sum_{j=c,m,o} kq \cdot \left| Q_j - Q_{cx} \right| \right)$$
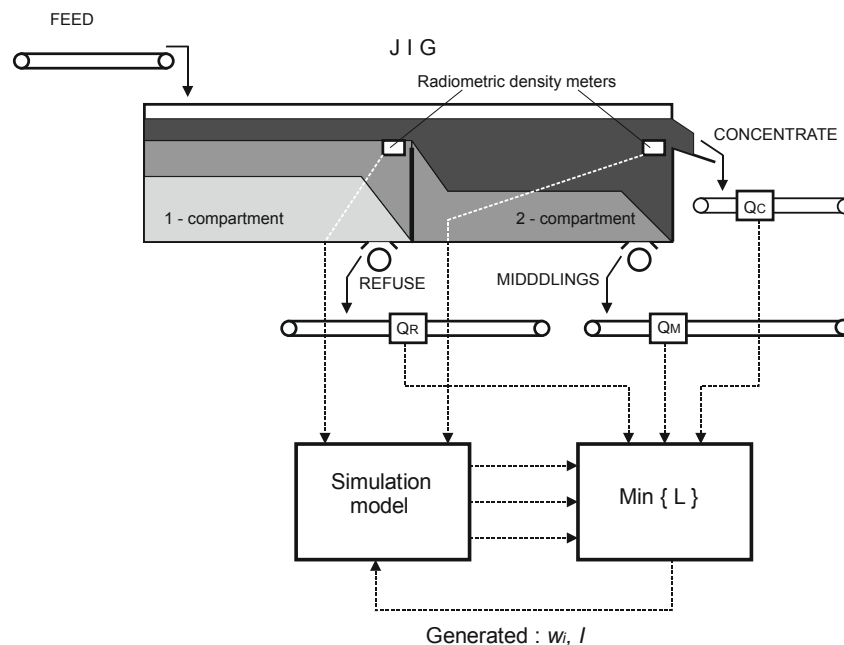
(12)

Fig. 9. On-line monitoring of the effectiveness of the coal separation process

Rys. 9. System monitoringu efektywności procesu wzbogacania węgla

As the function L can have a number of local extreme points, and as its minimum can be found for a number of combinations of parameters of this function, the algorithms based on gradient and evolutionary methods have been applied for the search of the optimum range (Goldberg 1998; Solver – Excel 2007, 2015). Simulated values of different sets of parameters for the identified process have been chosen from the following ranges:

◆ washability characteristics: $w_1 = 42 \pm 5\%$, $w_2 = 10 \pm 5\%$, $w_3 = 4 \pm 3\%$, $w_4 = 4 \pm 3\%$, $w_5 = 11 \pm 5\%$, $w_6 = 29 \pm 5\%$,

◆ separation densities: $\rho_{s1} = 1.4 \pm 0.25$ g/cm^3, $\rho_{s2} = 1.8 \pm 0.25$ g/cm^3,

◆ imperfection: $I = 0.1 - 0.2$.

Results of a simulation performed on 30 sets of parameters identified for the jig show that errors of determination (standard deviation) of 6 density fractions $w_1 - w_6$ are big and amount to 1.7–2.2% for light (w_1, w_2) and heavy (w_5, w_6) density fractions and ca. 1.5% for middlings (w_3, w_4). Better results can be achieved for light and heavy combined fractions. In this case, errors of identification (standard deviations) amount to 1.46% (for w_{1-2}), 1.15% (for w_{5-6}) and to 0.6% (for w_{3-4}). The error of identification (standard deviation) of imperfection I was 0.011. The average results of the simulation analysis performed for 30 sets of identified parameters are presented in Fig. 10.
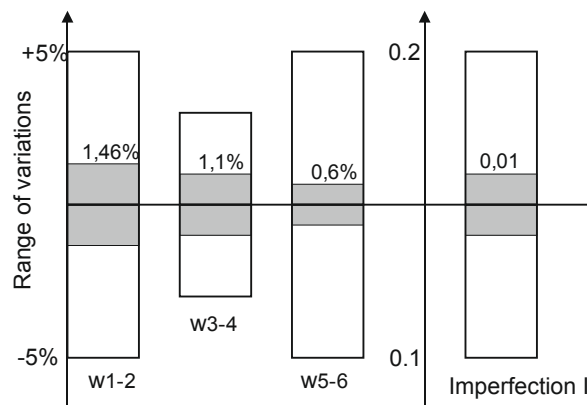

Fig. 10. Range of changes of identified parameters and errors of identification

Rys. 10. Zakres zmienności identyfikowanych parametrów i błędy identyfikacji

Conclusions

The simulation analysis has shown that the presented soft monitoring system can be successfully used in the complex identification of a coal separation process in a gravitational washer such as a jig. It seems to be a good method for the on-line determination of raw

coal washability characteristics, the partition characteristics of the machine and separation densities. Good results for three density fractions have been obtained. The results of the imperfection in soft monitoring show that it is possible to classify the efficiency of a jig into several ranges on-line, for example: very good, good, satisfactory, not satisfactory.

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SYSTEM MONITORINGU PROCESU WZBOGACANIA WĘGLA – BADANIA SYMULACYJNE

Słowa kluczowe

wzbogacanie węgla, osadzarka, efektywność procesu, monitoring parametrów procesu

Streszczenie

Modele symulacyjne są często stosowane w systemach monitoringu procesów technologicznych w celu oceny efektywności procesu oraz spełnienia procedur ilościowych i jakościowych. Istotnym obszarem zastosowań modeli symulacyjnych są procesy wzbogacania węgla i innych surowców mineralnych, w których informacja o przebiegu procesu uzyskiwana jest zwykle na podstawie pracochłonnych analiz laboratoryjnych próbek materiału pobranych z procesu. Węgiel surowy jest często wzbogacany w procesach grawitacyjnych w cieczach ciężkich i osadzarkach. Oba procesy modelowane są podobnymi charakterystykami wzbogacalności węgla oraz krzywymi rozdziału wzbogacalnika.

Koncepcja ciągłej identyfikacji charakterystyki wzbogacalności węgla i imperfekcji wzbogacalnika (osadzarki) polega na ciągłym porównywaniu sygnałów z trzech wag przenośnikowych oraz dwóch gęstościomierzy radiometrycznych (dla dwóch gęstości rozdziału) z sygnałami generowanymi

w modelu symulacyjnym procesu. Minimum odległości dwóch wektorów sygnałów pomiarowych i symulowanych wyznacza poszukiwane parametry procesu. Badania symulacyjne powyższego systemu monitoringu wykazały możliwość identyfikowania on-line trzech klas gęstościowych węgla surowego oraz imperfekcji trójproduktowej osadzarki.

ON-LINE MONITORING OF A COAL SEPARATION PROCESS IN A JIG – A SIMULATION STUDY

Keywords

coal preparation, jig, process effectiveness, parameters monitoring

Abstract

Simulation models are often used in "soft monitoring systems" to predict the effects of production and to diagnose whether the technological process meets the required standards over a given period. They also, however, show promise in the context of mineral and coal processing plants where information on process performance is typically gained from time and labor consuming laboratory tests on samples of material taken from the feed and products from the beneficiation process. Coal concentrates from raw coal are produced through gravitational separation processes in heavy media vessels and in jigs. Both processes are described by a similar model of raw coal washability characteristics and a partition curve of the machine. In soft monitoring used for the on-line identification of the partition curve (imperfection) and the washability characteristics, signals from the belt scales (yields of three products) and two separation densities from radiometric density meters are continuously compared at two different pairs of separation densities in a 3-product gravitational process in a jig, with similar signals generated in a simulation model of the process.

The simulation analysis has shown that the presented soft monitoring system can be successfully used in the complex identification of a coal separation process in a gravitational washer such as a jig. It seems to be a good method for on-line determination of raw coal washability characteristics, the partition characteristics of the machine and separation. Good results for three density fractions have been obtained. The results of the imperfection in soft monitoring show that it is possible to classify the efficiency of a jig into several ranges on-line, for example: very good, good, satisfactory, not satisfactory.