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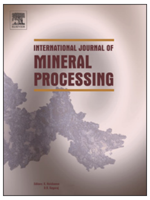

Strategies for control of parallel gravitational coal separation processes

S. Cierpisz

Institute of Innovative Technologies EMAG, 31 Leopolda, 40-189 Katowice, Poland

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ABSTRACT

The paper presents strategies for control of parallel gravitational coal separation processes in dense media vessels and jigs. These strategies are designed to maximize the yield of the final product at the desired ash content. The principle of circuits operating in parallel at equal incremental ash contents has been discussed from the point of view of its practical application. In the case of an ideal separation process this principle can be reduced to the requirement of equal separation densities for parallel circuits; so far, however, it has not been applied in real industrial processes. The paper includes a discussion on the concept of a separation density and incremental ash for computer simulation of parallel processes and their control. Conclusions from this discussion, presented in the paper are not available in open literature especially as regards the optimal control of jigs operating in parallel: (a) the separation density (elementary ash) defined as the density of the feed fraction reporting in half to the concentrate and in half to refuse and incremental ash (density of the elementary mass of material recovered in a process in which the yield is increased by an infinitesimally small amount) can be used for real time control in dense media baths and in jigs; (b) the autogenous separation process in jigs makes it possible to determine the incremental ash as the ash content in the separation layer of the material as measured by the correlation between ash content and the density of the separation layer. The concept of a new control system which may be used in practice, based on a radiometric density meter with a properly collimated radiation beam and located at the level of the separation layer has been discussed. The radiometric density meters, applied to monitor the density of the separation layer in jigs on-line and to monitor the density of heavy media in dense media baths can be used effectively in real-time control systems optimizing the yield of product.

1. Introduction

Raw coal is often beneficiated in separation processes in dense medium vessels (DMV) and dense medium cyclones (DMC), which apply manufactured medium in jigs (J) i.e. autogenous medium devices, and in flotation where physical and chemical properties of coal particles are used. Many authors in research literature use simulation algorithms to identify optimum set points in particular circuits (Gottfried et al., 1976; King, 2001). The majority of simulation software requires data regarding the washability of the feed and empirical partition. Optimization procedure usually aims at obtaining the maximum yield at the desired quality of product; this process can determine proper set points in each circuit. In processes which can be modeled by partition curves, the optimal set points are separation densities defined as densities of feed fractions which report in half to concentrate and in half to refuse. Unfortunately, such an approach cannot be applied in optimal control systems, because at present there are no methods available to monitor those parameters on-line in most separation processes. Only in the case of dense medium vessels can the separation density be approximately determined in relation to the density of the medium. Separation processes are often applied in parallel to wash varied coal size fractions effectively. Fig. 1 shows the typical configuration of such a technological system.

The following symbols are used in Fig. 1:

Q_i – flow rates of products from processes, % of the feed;
A_i – ash contents in products, %;
Q – flow rate of the final product, % of the feed;
A – ash content in the final product, %;
s_i – separation parameter in the process.

Flow rates Q_i and ash contents A_i in products can be set by controlling the separation parameters s_i which are (a) the density of the dense media in the case of DMV; (b) flow rates of the bottom product in the case of jigs; (c) the pressure gradient in DMC (Chu et al., 2009) and (d) a combination of reagent dose, amount of air and slurry level in a flotation process. The principle of the maximum yield Q at the desired ash content A for systems with parallel processes has been discussed by Cierpisz and Gottfried (1977), Salama (1989), Lyman

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E-mail address: s.cierpisz@ibemag.pl.

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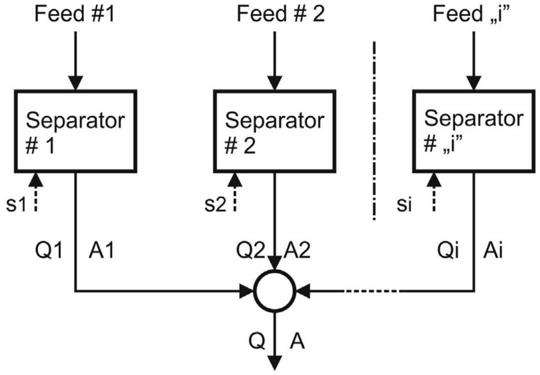

Fig. 1. Configuration of separation processes operating in parallel.

(1992), Luttrell and Mankosa (2002) and others. The principle has been derived from the basic mass balance formula (Cierpisz and Gottfried, 1977; Salama 1989):

$$Q = Q_1 + Q_2 + \ldots + Q_i \tag{1}$$

with the following constraint:

$$A = \frac{A_1 Q_1 + A_2 Q_2 + \ldots + A_i Q_i}{Q_1 + Q_2 + \ldots Q_i} \tag{2}$$

By applying the method of Lagrange multipliers to Eq. (1) with the constraint (Eq. (2)), we can obtain the condition for maximum Q for the given A (Cierpisz and Gottfried, 1977; Salama 1989). The main steps of the method are as follows:

Let us create a new unconstrained function:

$$\varphi = A \cdot \sum_{i=1}^{i} Q_i - \sum_{i=1}^{i} A_i Q_i = 0 \tag{3}$$

and a function Φ:

$$\Phi = Q + \lambda \cdot \varphi = \sum_{i=1}^{i} Q_i + \lambda \cdot \left\{ A \cdot \sum_{i=1}^{i} Q_i - \sum_{i=1}^{i} A_i Q_i \right\} \tag{4}$$

where λ is an undetermined constant (known as a Lagrange multiplier).

The necessary condition for maximum Q is:

$$\frac{\partial \phi}{\partial Q_1} = \frac{\partial \phi}{\partial Q_2} = \ldots = \frac{\partial \phi}{\partial Q_i} = 0 \tag{5}$$

By applying Eqs. (5) to (4) we obtain:

$$\begin{aligned} \frac{\partial \phi}{\partial Q_1} &= 1 + \lambda A - \lambda \frac{\partial (A_1 Q_1)}{\partial Q_1} = 0 \\ \frac{\partial \phi}{\partial Q_2} &= 1 + \lambda A - \lambda \frac{\partial (A_2 Q_2)}{\partial Q_2} = 0 \\ \frac{\partial \phi}{\partial Q_i} &= 1 + \lambda A - \lambda \frac{\partial (A_i Q_i)}{\partial Q_i} = 0 \end{aligned} \tag{6}$$

and

$$\frac{\partial (A_1 Q_1)}{\partial Q_1} = \frac{\partial (A_2 Q_2)}{\partial Q_2} = \ldots = \frac{\partial (A_i Q_i)}{\partial Q_i} \tag{7}$$

Eq. (7) gives a general principle for maximum of the yield Q at the desired ash content A. The principle requires the system to operate every parallel separation process at set points with the same slope of the output characteristics $AQ = \mathrm{f}(Q)$. The only requirement is that output characteristics $Q = \mathrm{f}(A)$ for each process is monotonous, which generally applies to all gravitational processes, dense media cyclones and flotation (Cierpisz and Gottfried, 1977). The principle presented by Eq. (7) is identical with the concept of equal incremental ash (Lyman, 1992; Luttrell and Mankosa, 2002) which will be discussed in Section 2 of this paper. In this principle, the product yield is highest when all parallel circuits are operated at the same incremental ash. This is true for any number of parallel circuits and is independent of the washability characteristics and the size composition of the feed.

Incremental ash can be thought of as the ash content in the last elementary mass of material recovered in a process in which the yield is increased by an infinitesimally small amount (Luttrell, 2013). Incremental ash can be determined from measurements of the density of dense media in the case of DMV (baths) of small imperfection (Luttrell and Mankosa, 2002), but for other processes the open literature reports no practical methods to monitor this parameter on-line. The aim of this paper is to propose a practical method of incremental ash on-line monitoring in jigs and to propose control systems which can perform real-time optimization of parallel circuits. The analysis is therefore limited to a combination of parallel circuits DMV–DMV, DMV–J and J–J shown in Fig. 2. The number of parallel circuits with DMV and J is not limited.

The following symbols are used in Fig. 2:

ρ_{dm} – density of the dense media, g/cm^3;

$q_{b1,2}$ – flow rate of the bottom product in a jig, % of the feed.

Flow rates $Q_{1,2}$ and ash contents $A_{1,2}$ in products can be set by controlling (a) the density of the dense media ρ_{dm1} and ρ_{dm2} in DMV, and (b) flow rates of the bottom product q_{b1} and q_{b2} in jigs.

2. Principle of the maximum product yield: interpretation

2.1. Dense medium separators

The practical application of the principle of the maximum product yield in coal preparation systems requires a detailed interpretation of control variables. Fig. 3 illustrates the process of coal separation in DMV. Raw coal properties are described by the washability characteristics $w_{1,2}(\rho_{f1,2})$, which determines yields $w_{1,2}$ of density fractions $\rho_{f1,2}$ and ash contents $a_{f1,2}$ in two streams of the raw coal fed to DMV washers.

The content of each density fraction $w_{1,2}(\rho_{f1,2})$ in the concentrate is defined as the product of the fraction yield in the feed and the partition number $f(\rho_{f1,2}, \rho_{s1,2})$ for the separation density $\rho_{s1,2}$. The yield of the concentrate $Q_{1,2}$ and cumulative ash content $A_{1,2}$ in the concentrate can be calculated from Eqs. (8) and (9):

$$Q_{1,2} = \int_0^\infty w_{1,2}\left(\rho_{f1,2}\right) f_{1,2}\left(\rho_{f1,2}, \rho_{s1,2}\right) d\rho_{1,2} \tag{8}$$

$$A_{1,2} = \frac{1}{Q_{1,2}} \int_0^\infty w_{1,2}\left(\rho_{f1,2}\right) f_{1,2}\left(\rho_{f1,2}, \rho_{s1,2}\right) a_{1,2} d\rho_{1,2} \tag{9}$$

From Eqs. (7), (8) and (9) for an ideal separation process in which $f_{1,2} = 1$ for $\rho_{f1,2}/\rho_{s1,2} < 1$ and $f_{1,2} = 0$ for $\rho_{f1,2}/\rho_{s1,2} > 1$ follows relation Eq. (10):

$$a_1 = \frac{\partial (A_1 Q_1)}{\partial Q_1} = \frac{\partial (A_2 Q_2)}{\partial Q_2} = a_2 \tag{10}$$

where $a_{1,2}$ is the ash content in the separation fraction of the density $\rho_{s1,2}$. For ideal separation $a_1 = a_2$ stands for the incremental ash in each process.

According to Eqs. (8)–(10) the maximum yield of concentrate Q for an ideal separation process is obtained for equal ash contents in separation fractions $[a_1(\rho_s) = a_2(\rho_s)]$ and their values chosen so that the ash content in the final product is A. This also means that, in ideal