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Coal dense medium separation dynamic and steady-state modelling for process control

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ABSTRACT

Coal dense medium separation is a popular beneficiation process used for the upgrading of coal ore into power station and metallurgical coal. The control systems used in coal beneficiation are often limited to localised regulatory control of feed rate and medium density. A coal dense medium separation process can benefit substantially from process control provided that a dynamic model for this process is available as was previously developed by the authors for a fine coal dense medium cyclone (DMC) circuit. In this paper, the previous model is adapted to a coarse coal DMC circuit and validated over a wider range of operating conditions using real plant data. The model is further validated by reducing it to steady-state to form a partition curve. This curve is then compared to one derived from actual production data. The derived model is able to provide an estimate of the DMC overflow coal product that should be sufficient for process control.

1. Introduction

A coal dense medium separation (DMS) plant makes use of the principle of density separation to upgrade mined coal and produce metallurgical coal or power station coal. The objective of the DMS plant operation is to produce coal product within a minimum quality specification and maximum possible yield (England et al., 2002). Meyer and Craig (2010) have indicated that coal DMS plants do not typically operate at steady state and that setpoint changes should be tracked appropriately in terms of ash content and yield. Almost all DMS plants are only automatically controlled at the regulatory control level in terms of medium density and ore feed rate and there are significant financial implications if the average yield and ash content of product coal can be controlled and optimised.

Dynamic process models for the coal DMS process are limited in the available published literature (Meyer and Craig, 2010). Steady-state models developed by Napier-Munn (1991) cannot be used for process control purposes due to the need for time-varying process variables. DMS process models developed by Lyman et al. (1982) and Lyman et al. (1983) show dynamic process simulations which only focus on the regulatory control aspects such as medium density. A linear relationship between medium density and product coal ash content is assumed. This linear relationship results in the model only working within a narrow medium density band and can be viewed as a limitation. The dynamic models developed by Meyer and Craig (2010) are detailed in such a way that they can be used to simulate time-varying coal product quality and throughput. These models are based on first principles using conservation of mass and mass of components (Stephanopoulos, 1984) and can be used for simulating and validating process control strategies for DMS circuits. The models developed in Meyer and Craig (2010) were validated by comparing their responses to experimental data obtained from a fine coal dense medium cyclone (DMC) circuit. These data were generated from step changes in medium density, and the resulting changes in product ash content were carefully observed.

This paper will focus on using the dynamic process models develop by Meyer and Craig (2010) for a fine coal DMC and identify and validate them using throughput and yield for a coarse DMC circuit. System identification (Ljung, 1987) is used to identify the developed models. Validation of the models are conducted with varying low pass filter cut-off frequencies to illustrate how the model fit varies by removing signal noise. The beneficiation process is similar to the fine circuit described in Meyer and Craig (2010), although the coarse cyclone equipment and operating conditions are different, with the yield being much higher than that of the fine cyclone.

Two experiments are performed to verify the models developed in this paper. Experiment one used a step change in throughput

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while medium density was kept constant. The second experiment used a step change in medium density while throughput was kept constant. These steps were found by searching historical production data for large input changes such that the derived models can be validated over a wide range of operating conditions. These input signals could possibly be made to better excite the dynamics in the process provided that the opportunity exists to manipulate the plant inputs in order to generate more sufficiently exciting input signals (Ljung, 1987).

The relationship between yield and ash through the washability characteristics of the coal (England et al., 2002) can be used to evaluate the quality of the coal product. Fig. 1 illustrates the typical inverse relationship between throughput and quality (Bauer and Craig, 2008). Using coal washability, a similar inverse relationship would occur between coal throughput and yield.

Additional validation for the dynamic models of Meyer and Craig (2010) are presented in Meyer and Craig (2011), where the DMC model was reduced to a steady-state model which represents a DMC partition curve. This paper will further validate the DMC model by reducing the dynamic model developed from each experiment described above into a steady-state partition curve.

With the dynamic DMS process models being identified and validated with a larger input–output data set, these models are now more suitable for process control than the models described in Meyer and Craig (2010, 2011). Bauer and Craig (2008) show that the process control method of choice is model predictive control (MPC) (Camacho and Bordons, 2004). The MPC makes use of a dynamic model to predict future outputs based on past inputs and outputs. Using a reference setpoint, calculated future errors are used by an optimiser with a cost function and process constraints to determine future process inputs.

Section 2 describes the DMS process and associated measurement assumptions that are used for dynamic modelling. A brief description of the model identification and steady-state reduction is given in Section 3. An explanation of the two experiments that were conducted is also given in this section. Simulation results from the two experiments are given in Section 4. The steady-state partition curve validation is also detailed in this section.

2. Process flow and measurements of the DMS process

The DMS process used by Meyer and Craig (2010) is for a fine cyclone circuit whereas the circuit analysed in this paper is of a coarse cyclone circuit. Various assumptions had to be made in order to perform the system identification for the new equipment parameters. These assumptions are detailed below.

The process flow diagram in Fig. 2 illustrates a two module DMS plant. The run-of-mine (ROM) coal ore is collected in a silo and fed to two different DMC modules through automatic feeders which can be controlled using a variable speed drive. The ROM coal is conveyed to a double deck screen where the oversize (+25 mm) is beneficiated using a drum separator. The feed rate of the silo feed

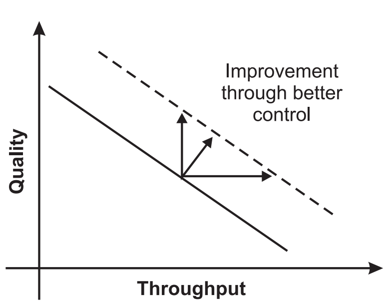

Fig. 1. General throughput versus quality relationship with improvement through better control (Bauer and Craig, 2008).

conveyor is measured and controlled using the automatic feeder. The middle-sized (−25 + 6 mm) ROM coal is fed into a mixing box which is mixed with magnetite medium and pumped into the coarse cyclone circuit. The coarse cyclone overflow and underflow material is washed with a drain-and-rinse screen. The drain-and-rinse screen is physically divided (using a barrier) into two streams to ensure the coal product and discard are not mixed. The drain-and-rinse screen is sized such that the medium is washed off the coal (overflow) and discard (underflow) and collected in a medium recovery circuit. The medium is ultimately circulated back into the mixing box. The medium is density controlled through the addition of water.

The undersize (−6 mm) ROM coal from the primary screen is processed further in the fine cyclone circuit. The detail of this process can be found in Meyer and Craig (2010). It must be noted that all of the sized product from each module is combined and screened. The final product from the coarse section is therefore combined for each module. The feed rate of the combined coarse material is measured. Similarly, all discarded material is combined and the reject mass flow rate is measured. As a result, certain assumptions have to be made to determine the individual module mass flow rates for the coarse product and discard material.

The control and instrument names used to describe the measurements in Fig. 2 are indicated in Table 1.

The following calculations indicated in Fig. 2 are described in Table 2.

The assumptions made to determine the calculated measurement points are as follows:

- The coarse material feed rate of module one is a composition of the coarse product and discard material weighted by the ratio of the feed of module one to the total plant feed. The discard material for the coarse feed is weighted according to the yield of the total coarse material.
- The combined coarse and fine material feed rate for module one is calculated as the difference between the primary screen feed and the oversize feed.
- The density of the module one coarse cyclone feed is proportional to the measured cyclone inlet pressure.
- The feed rate of coarse product for module one is weighted according to the total plant feed.
- The feed rate of coarse discard for module one is weighted according to the ratio of module one's feed to the total plant feed and the yield of the total coarse material.
- All calculations can be time-delay adjusted to ensure a single reference point in time for all measured variables. This can be accomplished by adjusting the measured output using either negative or positive time delays where applicable.

The calculated combined coarse and fine material feed rate C01 (kg/s) is given as,

$$\mathrm{C01}(t) = \mathrm{WIT1002}(t-\tau_{\mathrm{C01},i}) - \left(\frac{\mathrm{WIT1002}(t-\tau_{\mathrm{C01},i})}{\mathrm{WIT1002}(t-\tau_{\mathrm{C01},i})+\mathrm{WIT2002}(t-\tau_{\mathrm{C01},i})}\right)\mathrm{WIT0300}(t). \quad (1)$$

The time delay $\tau_{\mathrm{C01},i}$ is used to delay the feed ore [WIT1002(t) and WIT2002(t)] such that their measurements are synchronised with the measurements of the primary screen.

Mukherjee et al. (2003) have indicated that a gravity fed DMC can typically have a head height of between 9 and 11 times the cyclone diameter d. The relationship between relative density, pressure and head height is,

$$P = \rho g h, \quad (2)$$