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Modelling of vertical spindle mills. Part 1: Sub-models for comminution and classification

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HIGHLIGHTS

- Sub-models are developed for vertical spindle mill based on internal sampling data.
- An energy-based size reduction function is used for the VSM model.
- Elutriation is modelled based on an extended Rosin–Rammler efficiency curve.
- Air classifier is modelled based on the Sproull's gas cyclone model.

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ABSTRACT

A new mechanistic model for vertical spindle mills (VSM) has been developed by Julius Kruttschnitt Mineral Research Centre (JKMRC) at the University of Queensland. Unlike the previous work in the literature, which treats the VSM as a "black box", the present work incorporates two sets of variables in the model: (1) the coal specific property, and (2) the machine specific variables. The VSM model is presented in two parts/papers. The first part presents the sub-models for comminution and classification in the VSM. The second part describes the integration of the sub-models to simulate industrial scale E-Mill, MPS and CKP mills. The sub-models include mill power prediction, size specific energy calculation, size dependent breakage function, product size distribution estimation, elutriation classification and gas cyclone classification. The coal breakage property was measured with a JKFBC grinding device and modelled using a size-dependent breakage function. The machine specific variables include mill geometry, air classifier geometry, coal feed rate, primary air flow rate, air temperature, air pressure, grinding table rotational speed, mill spider hydraulic load and mill power draw. These variables are incorporated in the comminution and classification functions based on physical principles.

1. Introduction

In order to react effectively with oxygen from the air in a gas stream in coal power stations, typically the coal particle size needs to be at least 70% finer than 75 μm, with 99.5% of the particles needing to be finer than 300 μm. Grinding of coal to this level of fineness is referred to as coal pulverisation. The Vertical Spindle Mill (VSM) is one of the most popularly used grinding devices for pulverised fuel (PF) generation in coal-fired power stations worldwide. According to published figures, coal pulverisation is an energy intensive process. Approximately 0.5–1% of gross power generation from coal fired power stations is consumed in coal grinding, or approximately 40.5–81 billion kWh per annum based on the 8.1 trillion kWh world electricity generation by coal in 2010 [1].

A VSM typically incorporates a grinding unit and an air classifier in a confined mill shell, operated under elevated pressure and elevated temperature. Modelling a grinding facility is an effective approach for process optimisation. The literature shows that many attempts have been made in the past to model coal size reduction, such as Broadbent and Callcott [2,3] developing a matrix model, and Austin et al. [4] using a population balance model. Austin et al. [5] applied the population balance model to fit a laboratory E-type of ball-race VSM mill (modified from the standard HGI mill), and developed a model of grinding-classification to simulate a continuous Babcock E1.7 ball-race mill performance, using a scale up factor deduced from coal and air flow rates. Problems in running the simulations were identified. The authors commented: "The solution to these problems would require extended test work to establish a logical and quantitative basis for the variation of scale up factor with size distribution in the race".

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Sato et al. [6] used a roller-race mill, which employed three rollers to replace the eight grinding balls in the standard HGI mill, to conduct a series of grinding tests for various coals. The data were utilised to fit the population balance model parameters, using a similar approach to that of Austin et al. [5]. The fitted model parameters were scaled up to run simulations for a full scale VSM operation in steady state. Based on this work, Shoji et al. [7] further developed a dynamic model to do simulations for VSM at an unsteady state, again using breakage rate scale up factors. In these modelling processes, the mill was treated as a "black box", with its parameters being determined from the mill external sampling data (feed and ground product). As this modelling approach did not directly incorporate mill geometry data and operational conditions in describing the mechanisms of particle breakage, transportation and classification, its success in optimisation of the pulveriser operation was limited.

Sligar [8] developed a mill internal sampling technique to collect VSM internal stream samples. He then used the data to establish an empirical equation to link the selection function with mill geometry and operational conditions. This function was adopted by Robinson [9] in developing a model of transient operation of a coal pulveriser. Zhou et al. [10] also applied Sligar's work in modelling and simulation of a deep bowl pulveriser.

In recent years an extensive site campaign in Australian and Chinese power stations was conducted by teams from the Julius Kruttschnitt Mineral Research Centre (JKMRC) at the University of Queensland and the China University of Mining and Technology (CUMT), using a new sampling technique to collect both mill internal and external samples for case studies [11,12]. The data provide details of coal circulation inside the VSM, which assisted the development of mechanistic models for a ball-race mill (E-mill), roller-race mill (MPS) and roller-race mill without air classifier (CKP mill).

In the 1980s, the JKMRC developed the JKSimMet comminution simulation package for the minerals industry. This software platform enables models of processing equipment to be integrated with the material properties at various points in a circuit in order to simulate, predict and optimise the performance of different comminution and classification circuits. The JKSimMet package is widely used in the minerals industry [29]. A distinguishing feature of the JKMRC modelling technique is the decoupling of the machine and material parameters. This means that once the models are calibrated for a specific circuit, the circuit operating parameters can be optimised for different feed properties and blend ratios. The same modelling approach that has been successfully applied in the mineral industry was employed in developing a VSM model for the coal industry, as demonstrated in this paper. Part 1 of this paper presents the sub-models of comminution and classification functions, commonly associated with industrial vertical spindle mill operation. These sub-models are logically integrated to model the E-mill, MPS mill and CKP mill, which are presented in Part 2 of this paper.

2. Basic operational functions

The vertical spindle mill is named after its drive shaft orientation. A schematic of an E-mill VSM is shown in Fig. 1. The pulveriser is air-swept in which the coal is fed onto a rotating table through a central pipe. The coal is thrown outward by rotation into the grinding race. Seated in the race are ten 700 mm diameter steel balls (E-mill), or three rollers (MPS), which are held in the race by an upper stationary spider. The balls (or rollers) rotate with the table and pulverise the bed of coal that forms in the race, which is controlled partly by a hydraulic system that adjusts the grinding pressure exerted by the spider through the balls (or roller) on the table.

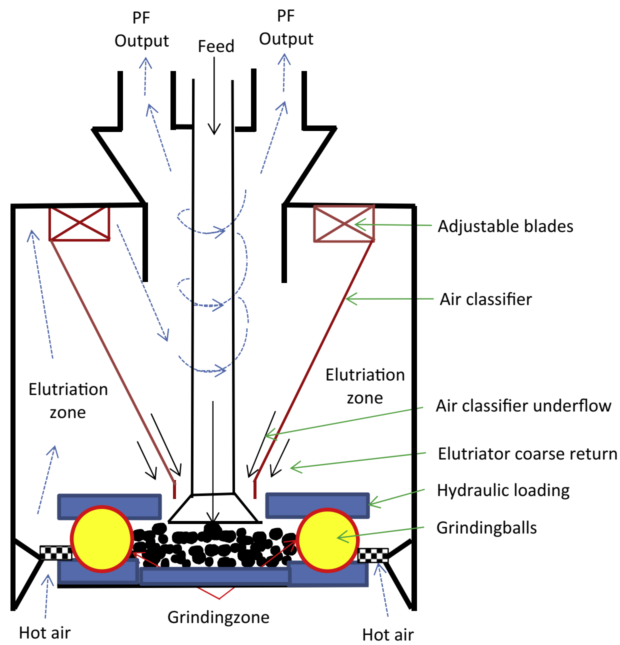

Fig. 1. Schematic of the grinding, elutriation and main classification zones in an E-mill.

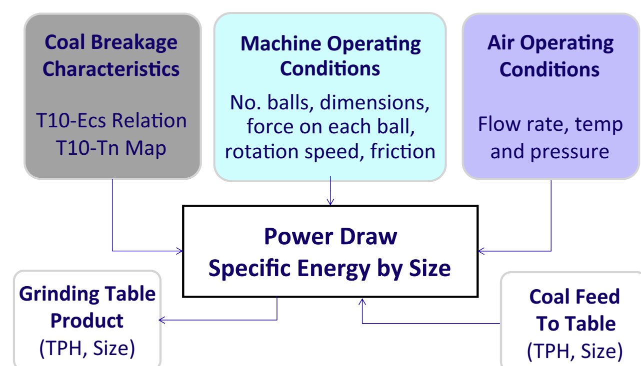

Fig. 2. Model algorithm structure for VSM comminution.

Both the ball-race and roller-race designs are arranged so that primary air enters the pulveriser through jets arranged circumferentially outside the grinding table, and where the ground coal is pushed radially outward into the primary air flow, which entrains the coal. Both pulverisers have two stages of classification in which oversize coal returns onto the grinding table and the final pulverised fuel will meet the required product size (70% < 75 μm).

The first stage of classification is a simple elutriator which effects a crude classification of large coal fragments which have a terminal velocity exceeding the upward air velocity at this point in the device. The second stage of classification is a true gas cyclone which operates with inlet vanes and relies on the swirl to further classify the coal.

Thus in operation a VSM consists of three basic functions: comminution, elutriator classification and gas cyclone classification.

3. Modelling of comminution

The comminution modelling focused on the development of sub-models for the breakage in the VSM. The algorithm structure for modelling comminution is presented in Fig. 2. There are three