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Research article

Ultrasonic technique for online measurement of bulk density of stamp charge coal cakes in coke plants

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ABSTRACT

Coke oven batteries utilize stamp charged coal cakes for production of high quality blast furnace coke. Crushed coal blends are mechanically stamped to produce coal cakes. It is crucial to have a good control over this stamping operation so as to achieve a uniform bulk density (≈1100–1200 kg·m^{-3} wet basis) of coal cake post stamping. This can facilitate robust and energy efficient coking operation. The dynamic nature of the stamping operation necessitates an online bulk density measurement technique. An ultrasonic technique which enables online measurement of bulk density during the stamping operation is described. The ultrasonic response was found to have a straight line correlation with bulk density (wet basis) and moisture content of stamped coal with an R^2 value of 0.98. The effect of moisture content in the coal on the ultrasonic measurements is also discussed. A lab scale prototype was developed with integrated sensors to emulate online measurement. The prototype was found to have a measurement error of less than ± 1.6%. This method can also be suitably adapted for online bulk density measurement of granular solids other than crushed coal.

1. Introduction

Coke plays multiple important functions in blast furnaces viz. fuel for smelting of iron ore, as a reducing agent, providing a porous structure for flow of gasses, molten metal and slag within the blast furnace burden etc. [1]. Coke is produced through destructive distillation of coal in coke oven batteries. The shortage of high grade coking coal postulates the use of blends of crushed low grade coals from various sources for coke making. These blends are usually compacted into cakes (of typical dimensions: 14 m × 5 m × 0.5 m) by means of stamping or pressing before being charged into the coke ovens to increase the bulk density (BD) of charged coal [2–9]. Bulk density of the charged coal is an important factor that influences the quality of produced coke, energy efficiency of the coking operation, cake stability and operating life of coke ovens [3,4,6–9].

1.1. Mechanical stamping and bulk density of coal cakes

Mechanical stamping of coal blends is one of the few processes used to increase the bulk density of charged coal [3,4,6–8]. The stamp charge process utilizes a stamping charging cum pushing (SCP) machine for mechanical compaction of crushed coal blends [7,8]. In the stamp charge process, the crushed coal blend is filled in a metallic stamping box of typical dimensions 14 m × 5 m × 0.5 m (Length × Height × Thickness) as shown in Fig. 1. A series of mechanical stampers are used to compact the coal blend in the stamping box. The number of stamps (n) required to achieve a particular bulk density of coal cake can be calculated as per Eqs. (1) and (2) [2,5,6].

$$E = \sum_{n}\left(\int_{s}^{s(F_{max})} F(s)ds + \int_{s(F_{max})}^{s_{max}} F(s)ds\right)_{n} \tag{1}$$

$$\rho_c = \rho_0\left(\frac{E}{E_0}\right)^{\frac{1}{K}} \tag{2}$$

where; E is the specific stamping energy to achieve a final bulk density ρ_c, E_0 is the specific stamping energy for an intermittent stamping step with bulk density ρ_0, maximum drop height of stamper s_{max}, intermittent height of stamped coal cake s and stampability of coal blend K.

It can be inferred that the calculation of the stamping energy and hence the number of stamps required for achieving a particular bulk density of coal closely depends on the stampability of coal which depends on various properties of the coal blend, viz. type of coals used, particle size distribution, moisture content, density of lump coal, ash content etc. Despite close controls on the preparation of the coal blends, it is not practically possible to achieve constant properties of the coal

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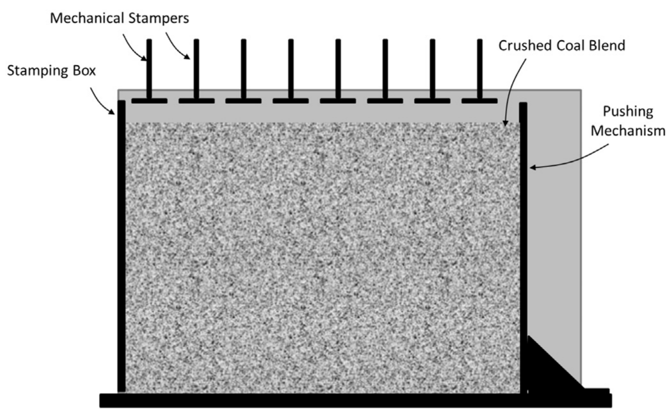

Fig. 1. Schematic representation of SCP machine operating elements.

blends due to the various sources of coals used for their preparation. This inherent inconsistency in properties of coal blends makes an approximation in the determination of the stampability factor *K* inevitable [2,5,6]. Due to the complexities involved, extensive laboratory studies are generally done to arrive at the stamping energy required to achieve a particular bulk density of coal cakes [2,5,6,10]. This makes it impossible to achieve the desired bulk density of coal cakes: neither uniformly throughout a particular stamped cake, nor constantly for various cakes stamped consecutively.

Achieving a particular bulk density, generally in the range of about 1100–1200 $kg \cdot m^{-3}$ (wet basis) depending on the properties of coal blend, uniformly throughout the coal cake is extremely critical to both the quality of coke produced and the efficiency of coking operation. The coal cake should be dense enough to achieve sufficient strength and at the same time have sufficient porosity for minimizing energy consumption in the oven during coking operation. A very high bulk density will result in excessive swelling of that region of the cake during coking operation within the oven. This will exert pressure on the side walls of the coke oven and damage the inner linings resulting in huge capital loss. On the contrary, a low bulk density will reduce the operational efficiency of coking oven and may even result in loss of stability of the coal cake, due to insufficient mechanical strength, causing it to collapse under its self-weight. The cumulative effect of all parameters including coal quality, particle size, moisture content, stamping/compacting process etc., is on the bulk density of the coal cake. Thus, any technique which enables continuous online measurement of bulk density profile of the coal cake during stamping can be utilized for proactive control of the stamping process. Such a control system can effectively aid in producing coal cakes with accurate and uniform bulk densities. This work describes an ultrasonic technique which enables accurate online measurement of bulk density of coal cakes. This will ultimately help in achieving higher quality coke with lower energy consumption.

1.2. State of the art

Common practice in most industries is to determine the stamping energy and hence the number stamps required to achieve a particular bulk density in a laboratory setup and scale it for industrial use. Other common practices involve (a) pushing the stamped cake onto a weighing platform and dividing this value by the volume of the coal cake by measuring its dimensions or (b) drilling a cylindrical core of known volume from the stamped cake and measuring its weight to calculate the bulk density. These methods however, cannot be used for continuous online measurement and dynamic control of stamping process.

Methods emulating the ISO 23499:2013 for offline determination of bulk density of un-compacted coal in laboratory environment for the use in charging of coke ovens are described in [11,12]. These methods involve practical difficulties; viz. (a) constant vibration of the SCP machine will hamper the functioning of the load cells and disallow accurate measurement of mass; (b) accurate measurement of dimensions of stamped coal cake is another issue as the height may not remain exactly same across the length of the coal cake, this will lead to inaccurate volume estimation. In addition, these methods cannot measure and locate regions with inhomogeneous bulk density within the cake. This information is crucial for achieving dynamic control of the stamping process.

Methods based on microwave attenuation and phase shift have also been explored by researchers for online moisture and bulk density measurements in corn husk for the food processing industry [13,14]. This technique poses certain practical limitation for the problem at hand. Microwave attenuation/reflection greatly depends on the dielectric constant of the material and is completely reflected by magnetic materials. The coal is stamped in a metallic stamping box, of the SCP machine, which will completely reflect the microwaves and prevent its interaction with the coal cake.

X-ray and neutron gamma ray based techniques have also been studied and used for industrial bulk density measurements [15,16]. These techniques however pose a significant radiation exposure hazard and require positive isolation which is highly undesirable.

The dependence between ultrasonic wave velocity, density and elastic properties of isotropic media is well established [17–19]. Similar relationships have also been studied for rigid porous media like wood, ceramics, cancellous bone etc. [20–23]. The nature of ultrasonic wave propagation in granular media, like hydrating cement, sand, etc. [24–26], have also been explored by researchers. Stamp charged coal cake is not highly rigid and can be considered as a compacted-hydrated-granular media. It is thus expected that similar relationship must exist between ultrasonic wave velocity and bulk density of stamp charged coal cakes. This work aims to ascertain this relationship for stamp charge coal cakes and suitably adapt it for online industrial application.

2. Methodology

It was aimed to mimic the processes in industrial stamping operation in lab scale for all experiments. A step by step account of the experimental procedure is described.

2.1. Preparation of coal blend

Coal blend from a single lot was selected so as to have constant properties for all experiments. The properties of the coal blend used are shown in Table 1a. The details of particle size distribution (sieve analysis) is shown in Table 1b. The coal blends are usually stored in an open atmosphere and hence subject to constant change in moisture content due to evaporation. It is thus essential to prepare the coal blends with the appropriate moisture content prior to every experiment. A coal moisture content of 10–12 wt% is considered to be the ideal range for stampability, cake strength and coking efficiency [5]. Thus, coal blends were prepared with 10–12 wt% moisture content for the study.

For preparing the coal blends with desired moisture content, the initial moisture content is measured using a moisture analyser as per

Table 1a
Properties of coal blend used for experiments (wet basis).

Property	Value
Ash content (%)	14.35
Volatile matter (%)	22.24
Crucible swelling number	5
Max. fluidity (DDPM)	12
Particle size (details in Table 1b)	90% below 3.15 mm
Moisture	10–12 wt%