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Mathematical modeling of blast furnace burden distribution with non-uniform descending speed

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ABSTRACT

The burden distribution is directly related to efficiency and stable blast furnace operation. In this paper, a mathematical model for estimating the burden distribution was developed with the combination of the falling curve sub-model, stock-line profile formation sub-model and burden descending sub-model. In a blast furnace, the burden descending velocity may be non-uniform along the radial direction due to the shaft angle and non-uniform consumption of the burden material. The modifications on two existing burden descending models, i.e., geometric profile (GP) model and potential flow (PF) model are proposed to consider non-uniform descending speed. The proposed non-uniform descending models are validated with published experiment results of scaled blast furnace. The accuracy increases notably for the modified models with the non-uniform descending velocity when compared with the original uniform descending model. In addition, the GP model and PF model are compared. The results produced by the two models are very similar. For modeling the burden descending process, both the GP model and the PF model could predict the burden profile in the upper part of the shaft. However, the PF model is capable to capture the burden distribution in case of irregular wall geometry such as scab buildup and erosion of the refractory. The effects of the non-uniform descending velocity on burden distribution in blast furnace are discussed.

1. Introduction

Within a blast furnace, the burden distribution plays an important role because it influences the formation, shape and location of cohesive zone, which are essential for the gas flow distribution and the furnace efficiency. Therefore, an appropriate control of the burden distribution is required for smooth blast furnace operation. In order to predict the burden distribution, both the charging and descending process need to be considered since burden distribution is a continuous process. Nowadays, Bell-less charging equipment was installed in most of the commercial blast furnaces due to the excellent controllability. Technically, the formation of the burden structure consists of three main steps by sequence. In the bell-less blast furnace, the first step involves the descent of the material from the discharge hopper, movement along the chute, detachment and falling of the raw material from the rotating chute. To investigate the trajectory of the raw material and the impact points at the stock line, the falling trajectory has been studied theoretically and experimentally. Nag and Koranne [1] reported measurements taken from plant during the filling of a commercial blast furnace. The small-scale experiment model

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Nomenclature

D_0	throat diameter, m
L	vertical distance of the burden profile, m
L_t	throat height, m
S_i	cross-section area, m^2
ΔV	burden moving volume in one time step, m^3
$V_{s,y}$	burden vertical velocity, m/s
$V_{s,r}$	burden radial velocity, m/s
K_b	relative velocity factor
c_α	rolling coefficient
r	radial distance of the burden profile, m
α	shaft angle, $^\circ$
β_o	outer Angle of repose, $^\circ$
β_i	inner Angle of repose, $^\circ$
θ	chute angle, $^\circ$
ρ	burden density, kg/m^3
ϕ_s	burden velocity potential, m^2/s

was reported by Liang et al. [2]. The single particle model was developed and extensively compared with experimental data and to investigate the effects of the chute parameters [3–5]. A detailed force and velocity analysis along the chute was carried out by Nag and Koranne [1] and Kondoh [6]. Secondly, with the information of the trajectory from the first step, the shape of the ring formed on pervious stock profile can be defined, thus the new stock profile is available by adding the successive rings of the entire charging. Jiménez et al. [7] reported a semicircle 1/10 shaft cold experimental model and used camera to capture the ring shape of each dump. Mathematical models were also developed by Jiménez et al. [8] to simulate the ring profile by a pair of second degree polynomials. Matsuzaki [9] proposed that the normal distribution function can be used to describe the heap up ring profile. A real-time estimation of the burden distribution was achieved using multi-radar data [10]. Finally, the charged burden redistributes as it moves downward to form the entire burden structure. Studies were conducted on the descending behavior of burden. In terms of experiment, the burden structure was measured in a warm experiment carried out by Ichida et al. [11]. Nishio et al. [12] originally proposed the GP model by a uniform descending speed. The descending rate inside the burden could be affected by the charging conditions as well as the chemical and physical changes of burden material inside the furnace. Limited technology exists to detect the burden distribution and burden descending rate below the burden surface. However, the surface descending velocity is affected by the internal state of the whole burden. It is unusually non-uniform along the radius of the furnace. The operation condition of the blast furnace strongly influences the burden redistribution due to the local solid consumption [13,14], i.e., ore reduction and coke gasification. Ichida et al. [15] measured the non-uniform distribution of burden descending velocity along the radius and further proposed a non-uniform descending model. However, the non-uniform descending model proposed by Ichida et al. [15] assumes a step change of the velocity which does not account for continuous changing along the radius. In this paper, the modifications on two existing burden descending models, i.e., geometric profile (GP) model and potential flow (PF) model are proposed to consider the non-uniform descending speed.

The main objective of the paper is twofold: to combine the three sub-models including prediction of falling curve trajectory, stock-line profile and burden descent for modeling the entire burden formation process by taking the non-uniform descending velocity into consideration, and to validate the established model by comparing with published experimental data.

2. Mathematical model

2.1. Falling curve sub-model

The falling curve of the material (trajectory) during charging from rotating chute is described by a single particle model which considers force balance [5]. The gravitational force, centrifugal force and frictional force are considered in the model. The model describes the movement of the raw material including discharging from the hopper, sliding along the rotating chute and free fall from the chute tip to the impact point of the stock profile.

2.2. Stock-line profile formation sub-model

The stock profile is determined in the following steps as shown in Fig. 1. In Fig. 1(a), with each revolving of the chute, the raw material falls on the stock line to form a ring shaped heap. The cross-section of the heap is assumed to be triangular shape where the apex of the triangle is on the falling curve trajectory. The triangle shape is determined by the inner angle