MATHEMATICAL 3D MODEL OF MOTION OF BURDEN MATERIALS IN THE BELL-LESS BLAST FURNACE TOP AFTER LEAVING THE ROTATING CHUTE

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Abstract

Last year we presented the mathematical model of the motion of burden materials in the bell-less blast furnace top of the type Paul Wurth or Vitkovice. The article from previous year concerned namely with one phase of the motion - motion at the rotating chute. In the actual article we continue with describing of following phase of the motion - downfall of burden materials after leaving the rotating chute.

Keywords: Blast furnace, bell-less top, 3D mathematical model

1. INTRODUCTION

This article closely relates to our article from the last year [1] where we concerned with one of basal phases of the motion of burden materials poured into the blast furnace equipped with the bell-less top of the type *Vítkovice* or *Paul Wurth*. The cardinal part of both of them is the rotary and foldable chute. In the introduction of [1] we described principles of functioning of both top types as well as fundamental differences in their work. Both articles result from the original mathematical model published already in [2] and [3]. This initial mathematical model comprehended only two basal phases of the motion of burden materials in the bell-less top - the motion of burden materials at the top chute and falling of these after leaving the chute. The phase *falling of burden materials after leaving the top chute* covers the motion of burden materials from the moment of leaving the chute to impact of these to upper stock layers. Thus, this phase immediately concurs to the phase described in [2].

Falling of burden materials after leaving the top chute was described in the initial mathematical model only by the kinetic equation of a single representative particle. The front gas resistance during the fall after leaving the chute cannot be generally neglected unlike it was possible for the motion at the chute. Because particles moving at the chute are parts of a coherent layer the front gas resistance for single particle is equal to zero. By contrast, after leaving the chute single particles are not parts of any coherent flow namely by the top gas flow incidence. That's why especially little particles can be considerable influenced by front resistance of gaseous environment.

2. FORMULATION OF THE PROBLEM, COORDINATE SYSTEMS AND MARKING

Falling of bigger particle for that the front gas resistance can be neglected represents in physical view a simple skew shot, i.e. a plane motion in a vertical falling plane. The vertical falling plane is given by the initial point and by the initial velocity, i.e. by the point in which the material leaves the chute tip and by its velocity in this point. Because the direction of the top gas contraflow is generally vertical either smaller particle for which the front gas resistance already cannot be neglected is to be moving in the same falling plane. But the trajectory of such particle motion is not a ballistic curve because the direction of front resistance of gaseous environment is generally different from the direction of the particle velocity. Extremely small particles (e.g. dust particles) can be even flushed away by the top gas flow.

For mentioned assumptions the fall of burden materials after leaving the chute represents a 2D problem in the falling plane. But the data from the vertical falling plane cannot be directly used to determinate the particle location in the top. The falling plane generally does not contain the top axis and this plane concrete location depends on more factors. To determine the particle location after leaving the chute as well as to describe the burden layers depositing the cylindrical coordinate system *{φ, r, H}* seems to be the most sufficient, where

- φ is the angle of the general half plane, i.e. the coordinate half plane bounded by the top axis,
- r is the distance from the top axis,
- H is the distance from a specific plane, usually from the plane called the technological zero.

In following the coordinate system *{φ, r, H}* is denoted as the *top coordinate system*. In the top coordinate system we solve again the 3D problem. But in the kinetic equation of a single representative particle notation we prefer the Cartesian coordinate system - especially the *falling plane coordinate system* which's the first axis is horizontal, lies in the falling plane and intersects the vertical axis in the point *O* where the particle leaves the chute. Thus, the origin *O* of this coordinate system depends on the result of the first phase of the particle falling.

In arbitrary Cartesian coordinate system firmly connected with the top the moving particle is influenced by a non-conservative system of three forces - the force of gravity $\boldsymbol{F}_g$, the force of static buoyancy and the force of front resistance of environment $\boldsymbol{E}$.

In consequence of concrete conditions and of comparison with the force of gravity the force of static buoyancy can be entirely neglected. But the force of front resistance of environment cannot be generally neglected because particles of burden materials are influenced by the chute rotation and thus don't create sufficiently coherent flow. Mentioned conditions enable to formulate the kinetic equation of the motion of a particle

$$m \cdot \frac{d^2\mathbf{p}}{dt^2} = \mathbf{F}_g + \mathbf{E} \quad , \tag{1}$$

with initial conditions

$$\mathbf{p}(t_{out}) = \mathbf{p}_{out} \quad , \quad \frac{d\mathbf{p}}{dt}(t_{out}) = \mathbf{v}_{out} \quad . \tag{2}$$

In following review we introduce notation used in the kinetic equation and in initial conditions as well as in other equations and expressions (e.g. the transformation of the problem solution from the falling plane coordinate system to the top coordinate system), see also **Fig. 1**:

- $\boldsymbol{p}$ position vector of a particle in the Cartesian top coordinate system or directly in the falling plane coordinate system, respectively,
- m mass of a particle,
- $\boldsymbol{g}$ acceleration due to gravity (g denotes magnitude of vector $\boldsymbol{g}$),
- t time,
- t_{out} time in that a particle leaves the chute,
- $\boldsymbol{\omega}$ angular velocity of the chute ($\omega = 2\pi \cdot f$ where f is frequency of the chute rotation),
- $\boldsymbol{v}_\omega$ velocity of the chute tip with respect to the top in time t_{out},
- $\boldsymbol{v'}$ velocity of a particle with respect to the chute, $\boldsymbol{v'}_{out} = \boldsymbol{v'}(t_{out})$,
- $\boldsymbol{v}$ velocity of a particle with respect to the, $\boldsymbol{v}_{out} = \boldsymbol{v}(t_{out})$, $\boldsymbol{v}_{out} = \boldsymbol{v'}_{out} + \boldsymbol{v}_\omega$,
- $\boldsymbol{v}_g$ velocity of the top gas in corresponding point of the top (with respect to the top),
- $\boldsymbol{v}_r$ velocity of a particle with respect to the top gas flow, i.e. $\mathbf{v_r} = \mathbf{v} - \mathbf{v_g}$,
- v_x horizontal component of the velocity $\boldsymbol{v}$,
- v_{x1} horizontal radial component of the velocity $\boldsymbol{v}$,
- v_{x2} horizontal transversal component of the velocity $\boldsymbol{v}$,
- v_y vertical component of the velocity $\boldsymbol{v}$,

β angle between the falling plane of a particle and the general half plane given by the point in which the particle leaves the chute,

r_{out}, H_{out} coordinates r, H of the chute tip for $t = t_{out}$.

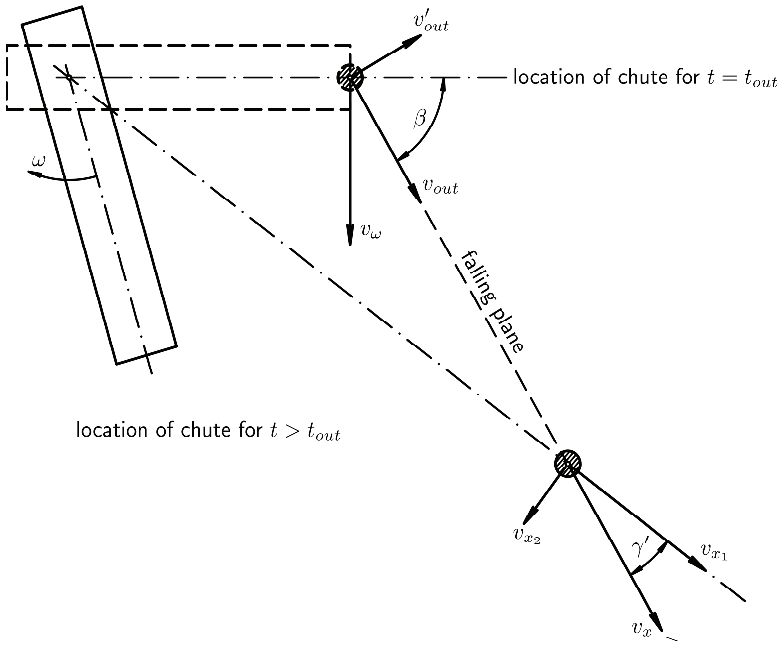

Fig. 1 Simplified floor projection of falling of a particle after leaving the chute

3. CONCRETIZATION OF THE KINETIC EQUATION AND PROPOSAL FOR OUTPUT PROCESSING

The force of gravity $\boldsymbol{F_g}$ in the equation (1) is vertical and is given by relation

$$\mathbf{F}_g = m \cdot \mathbf{g} \quad . \tag{3}$$

The force of front resistance of environment $\boldsymbol{E}$ in the equation (1) antagonizes the motion of a particle with respect to the top gas flow. The direction of the force $\boldsymbol{E}$ is equal to the direction of the relative velocity $\boldsymbol{v_r}$ of a particle with respect to the top gas flow. The magnitude of velocity $\boldsymbol{v_r}$ must be also used to calculate the magnitude of the force $\boldsymbol{E}$.

Assuming vertical direction of the top gas velocity the fall of a particle proceeds in the same falling plane as if the environment resistance could be neglected.

Dependence of the magnitude E of the force $\boldsymbol{E}$ is very complex problem in general. Relationship between laminar and turbulent flow character depends on many factors, especially on physical properties of a particle and on relative velocity of a particle with respect to environment. The Newton's relation

$$E = m \cdot k \cdot v_r^2 \tag{4}$$

serves the purpose for objective conditions in the blast furnace. There k is constant of proportionality dependent on shape, characteristic size and density of a particle and on density of environment.

For assumptions mentioned above the force $\boldsymbol{E}$ satisfies equation

$$\mathbf{E} = m \cdot k \cdot \left|\mathbf{v}_r\right|^2 \cdot \frac{-\mathbf{v}_r}{\left|\mathbf{v}_r\right|} = -m \cdot k \cdot \left|\mathbf{v} - \mathbf{v}_g\right| \cdot \left(\mathbf{v} - \mathbf{v}_g\right) \quad . \tag{5}$$

The kinetic equation (1) comes after substitution and rearrangement into form

$$\frac{d^2\mathbf{p}}{dt^2} = \mathbf{g} - k \cdot \left|\mathbf{v} - \mathbf{v}_g\right| \cdot \left(\mathbf{v} - \mathbf{v}_g\right) \quad , \tag{6}$$

where

$$\mathbf{v} = \frac{d\mathbf{p}}{dt} \quad . \tag{7}$$

Thus, the kinetic equation (6) can be written in form

$$\frac{d\mathbf{v}}{dt} = \mathbf{g} - k \cdot \left|\mathbf{v} - \mathbf{v}_g\right| \cdot \left(\mathbf{v} - \mathbf{v}_g\right) \tag{8}$$

with initial condition

$$\mathbf{v}\left(t_{out}\right) = \mathbf{v}_{out} \quad , \tag{9}$$

whereas the position vector $\boldsymbol{p}$ satisfies

$$\mathbf{p}(t) = \mathbf{p}_{out} + \int_{t_{out}}^{t} \mathbf{v}(t) \cdot dt \quad . \tag{10}$$

The result of mathematical modelling is the ascertaining that the force of environment resistance influences only trajectory of very small particles. Such particles are usually removed from the stock but other can be made later during burdening.

If the environment resistance is neglected the motion of a particle is in physical point of view the simple skew shot and its trajectory is a part of appropriate quadratic parabola. But the tangent in the initial point of this trajectory is generally not parallel to the cylindrical surface of the chute (simpler mathematical models e.g. [5] consider the direction of the material velocity at the chute to be equal to the direction of the longitudinal chute axis).

In Cartesian falling plane coordinate system the data of positon and velocity of a particle after leaving the chute can by relatively simply obtained. However cylindrical coordinate system of the top appears to be much suitable to describe the position $\boldsymbol{p} = (p_x, p_y)$ of a particle (**Fig. 1**):

$$r = \sqrt{r_{out}^2 + p_x^2 + 2 \cdot r_{out} \cdot p_x \cdot \cos\beta} \quad , \tag{11}$$

$$H = H_{out} + p_y \quad . \tag{12}$$

In other considerations of the motion of a particle after impact on the top surface or on burden layer we advantageously use separation of horizontal component v_x of the velocity $\boldsymbol{v} = (v_x, v_y)$ of a particle into radial component v_{x1} and transversal component v_{x2} (**Fig. 1**), for example

$$v_{x1} = v_{x1} \cdot \cos\gamma' = v_{x1} \cdot \frac{r_{out} \cdot \sin\beta}{p_x} \quad . \tag{13}$$

4. ACENTRAL FALL

One of results of the mentioned mathematical model use is detection of sources of *acentral fall* that can evoke large non-uniformity of burden distribution.

Calculations for discrete angle positions of the chute in the bell-less top of the type *Vítkovice* require implementation of function

$$r = f(H) \quad , \tag{14}$$

that indicates how the radius r of the stock ridge depends on the depth H if other parameters of material pouring are constant. This function is usually (and roughly) called *falling curve.* In our mathematical model the distance r of a particle is function of the depth H.

The mathematical model verity was compared with outputs of experimental measurements from the very beginning. But *empiric* (measured) falling curves and *theoretical* (computed) ones were sometimes significantly different. One of causes of these differences could be measuring inaccuracies. Only small number of measured data was available to obtain empiric curves, so inaccuracy of even only one of these could significantly influence the resulting curve.

Other cardinal source of mentioned differences between empiric and theoretical curves was detected just with the help of the introduced mathematical model. During modelling we found that resulting falling curve could be significantly influenced by initial conditions of the burden materials motion at the chute. The flow of burden materials is falling from the not centrally situated stack and does not impact the chute centrally, i.e. the axis of the burden materials flow is not equal to the axis of the top (that's why we use the term acentral fall). In consequence of acentral fall, initial conditions of the motion at the chute change during one revolution of the chute. Hence particles leave the chute with various velocities (with respect to the chute) during one revolution of the chute. Namely differences of velocity directions are very significant because these influence the magnitude of angle β and consequently even the form of the $r = f(H)$. Differences between empiric and theoretical curve then can be caused by using points that belong to various theoretical curves to create one resulting empiric curve.

If the upper surface of burden stock was a plane than the stock ridge built up during one revolution of the chute with constant inclination would not, in consequence of acentral fall, represent a circle with the circumcenter on the top axis. Such stock ridge would roughly have a shape of a circle but its circumcenter would lie outside the top axis. An effect of acentral fall then could be sizable differences of ratio *ore/coke* distribution in different axis cuts of the top. Sizable differences are especially produced in situation when the top is equipped with two stacks and one stack is used for coke whereas the other stack is used for ore.

5. CONCLUSION

Presented mathematical model describes in simplified form only two basal phases of the motion of burden materials in a bell-less blast furnace top. Results of calculation considerably depend not only on initial data but also on other parameters whereas some of these parameters are largely problematic. The model itself does not enable to obtain sufficiently precise information on real stock distribution. But the model enables to analyze outputs of realized measuring or respectively to complete measured outputs. Furthermore, the model enables to study how individual parameters influence the resulting burden distribution. With the help of the model the phenomenon of acentral fall was established and described.

REFERENCES

[1] KRČEK B. Mathematical 3D Model of Motion of Burden Materials at a Chute of a Bell-less Blast Furnace Top. In.: METAL 2014: 23nd International Conference on Metallurgy and Materials. Ostrava: TANGER, 2014, pp. 5, 2709.pdf.

[2] KRČEK B. et al. Mathematical Model of the Burden Materials Motion in a Bell-less Blast Furnace Top. In.: Hutnické listy, 1977, No. 7, pp. 466-470. (in Czech: *Matematický model pohybu vsázkových surovin v bezzvonové sazebně*)

[3] KRČEK B., BROŽ L. Usage of the Mathematical Model of the Burden Materials Motion in a Bell-less Blast Furnace Top. In.: Hutnické listy, 1978, No. 7, pp. 466-471. (in Czech: *O využití matematického modelu pohybu vsázkových surovin v bezzvonové sazebně*)

[4] KRČEK B. Mathematical Model of the Burden Materials Motion in a Bell-less Blast Furnace Top. CSc.-thesis, VSB, Ostrava 1987, 141 p. (in Czech: *Matematický model pohybu vsázkových surovin v bezzvonové sazebně*)

[5] YU Y.W., BAI C.G., ZHANG Z.R., WANG F., LV D.G., PAN C. Theoretical calculation and validation of burden trajectory in bell-less top blast furnace. In.: Ironmaking and Steelmaking, 2009, No. 7, pp. 505-508.