MATHEMATICAL 3D MODEL OF MOTION OF BURDEN MATERIALS AT A CHUTE OF A BELL-LESS BLAST FURNACE TOP

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Abstract

The bell-less blast furnace tops of the type *Paul Wurth* or *Vitkovice*, i.e. the bell-less tops equipped with a rotary chute, enable effective management of the blast furnace burdening. The calculations using the sufficiently true mathematical model make possible to reduce the number of difficult and expensive experiments to obtain the needed management data. The motion of burden materials in the bell-less top can be formally separated into several phases. One of the crucial phases is just the motion of burden materials at the chute of the bell-less top.

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

1. INTRODUCTION

All blast furnaces in the Czech Republic are presently equipped with the bell-less top of the type *Vítkovice*. The charging system of this bell-less top is in principle the same as the charging system of the type *Paul Wurth*. The cardinal part of both of them is the rotary and foldable chute. Burden materials that are prepared in one stack of the bell-less top are poured into the blast furnace in the interval from 5 to 8 rotations of the chute. In contrast to *Paul Wurth* type tops the angle of the chute inclination in a top of the type *Vítkovice* cannot be changed continuously through the chute rotation but only in one position of the chute. In ideal situation the poured stock corresponding to one revolution of the chute represents a circle whereas for the *Paul Wurth* type system could make a helix.

The bell-less top of the type *Vítkovice* was developed and started to work on one blast furnace already in the 70's of the last century. When developing the bell-less top charging system of this type the burden materials distribution in the top was extensively researched using a 1:1 scale model in which the original prototype of charging system was advantaged. After experiments when the model had already been taken down the charging system was significantly modified and performed changes in construction could considerably influence trajectories of poured materials. Because it was impossible to realize other necessary experiments and measuring, these had to be replaced with calculations and thence the sufficiently true mathematical model of the burden materials motion in the bell-less top had to be developed.

Considering extensive time and financial severity of real measuring the necessity of using a mathematical model to replace at least some measuring arose already from the very beginning of the *Vítkovice* bell-less top development. When using measured parameters for conveniently selected angles of inclination of the chute the data of trajectories for the other angles of inclination could be obtained through a statistical model, for example.

The mentioned modifications of the charging system construction caused such changes of the chute tilting geometry that the active length of the chute and its mouth position considerably came round as well as parameters of appropriate trajectories. Therefore only simple statistical processing of measured parameters made no sense.

In view of these facts the required mathematical model of the burden materials motion in the bell-less top has to be applicable for arbitrary chute tilting geometry and length. Such requirements are satisfied using the mechanistic model that is consistently based on physical principles. Hence, this model must be three-dimensional, even the model of the burden materials motion at the chute must already be three-dimensional. To calculate parameters of pouring trajectories we have to know not only the speed but even the direction of the speed of the burden materials leaving the chute.

Trajectories of larger pieces of burden material leaving the chute are approximately represented by quadratic parabolas (if the resistance of environment can be neglected). Because the falling plane generally does not involve the axis of the top the dependence of the downfall depth on the distance from the top axis is not quadratic function. The falling plane is vertical and is given by the point in which the material leaves the chute tip and by its velocity. The velocity of a material leaving the chute tip relating to the top is a vector sum of the velocity of the material relating to the chute and the velocity of the chute tip relating to the top. The direction of the motion of a material at the chute could significantly differ from the direction of the longitudinal axis of the chute. Therefore, to ensure sufficient accuracy of calculations the model of such motion must necessarily be three-dimensional.

2. MATHEMATICAL MODEL

The development of relevant mathematical models that have been published since 1978 is described in [1]. But the earliest 3D mathematical model developed by this article author was published already in 1977 [2]. The mathematical model of the burden materials motion presented in [2] and [3] describes two basal phases of the motion of burden materials in the bell-less top: the motion of a material at the chute and its downfall after leaving the chute tip. In later model [4] the motion of burden materials in the bell-less top was separated into 12 phases given by geometry of the top construction and by running physical actions. In addition to basal phases comprising among others also both mentioned phases, greater attention is in [4] paid to some transitional phases that take only very short time interval but that describe extensive changes of material velocity vector direction or magnitude. One of these transitional phases is the impact of burden materials at the chute, for example.

The motion of burden materials at the top chute was described in [2] and [3] by means of vector kinetic equation for a single hypothetic of particle having negligible size in comparison with the size of the chute; moreover, this particle does not roll on the chute, but slides, and the front gas resistance is equal to zero. Presented simplifications was namely based on observations of the motion of the actual burden materials supplied to the chute of the 1:1 scale model of a blast furnace top. These observations demonstrated that the solids moved in lamellar fashion along the entire length of the chute and created continuous slipping layer and that the front resistance of gaseous environment was entirely negligible.

To describe the motion of burden materials at the top chute special coordinate system called coordinate system of chute is used. This is Cartesian coordinate system firmly connected with the chute that rotates with the chute around the axis of the top with a constant angular velocity $\boldsymbol{\omega}$ that's magnitude ω is given by

$$\omega = 2\pi \cdot f \quad ,$$

where f is frequency of the chute rotation.

The coordinate system of chute is non-inertial system from the physical point of view. In this system the moving particle is influenced by a non-conservative system of forces subjected to a linkage (see fig.1 and fig.2) that consists of the external conservative force (force of gravity $\boldsymbol{F}_g$) and fictive forces (the centrifugal force $\boldsymbol{F}_r$ and the Coriolis force $\boldsymbol{F}_C$). When the particle impacts the chute, the system must be added by the force $\boldsymbol{F}_n$ (the force of reaction of the chute to the particle force acting) and by the non-conservative dissipation force $\boldsymbol{F}_t$ (induced by friction).

Moreover, the following nomenclature and designation will be applied:

α	angle of inclination of the chute measured from the horizontal plane (for a top of the type *Paul Wurth* α is angle between the chute and the axis of the top),
t	time,
t_0	initial time of motion of a particle on the chute,
m	mass of a particle,
g	acceleration due to gravity,
O	origin of a coordinate system with axis o_x, o_y, o_z ,
p	position vector of a particle, in physics it is usually denoted **s**, **s** = **p** = (x,y,z),
n	unit normal vector to the surface of the chute in the point given by the position of a particle,
r	distance of a particle from the axis of the chute rotation (i.e. from the axis of the top).

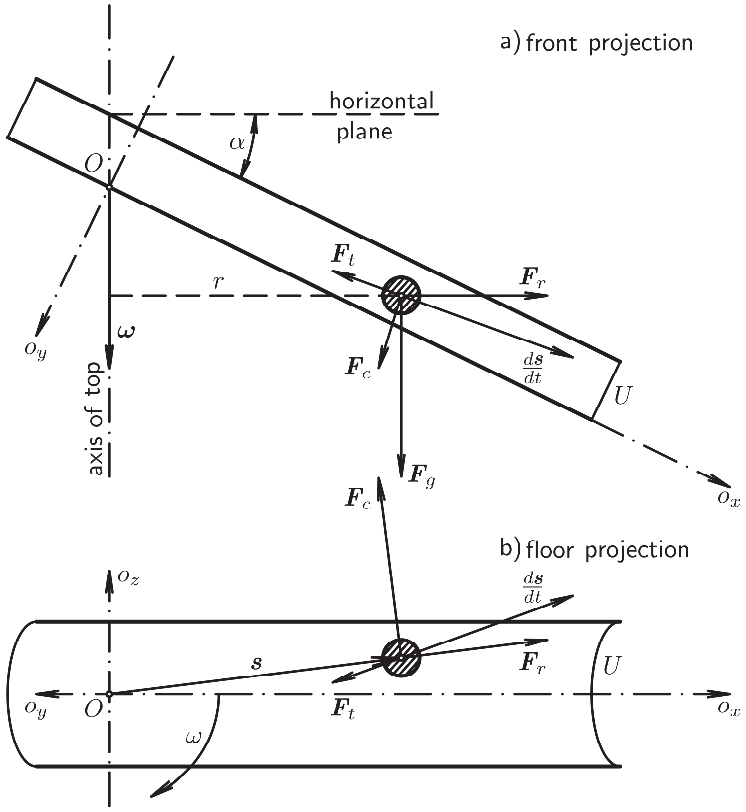

Fig. 1 Forces influencing a particle that is moving at the top chute

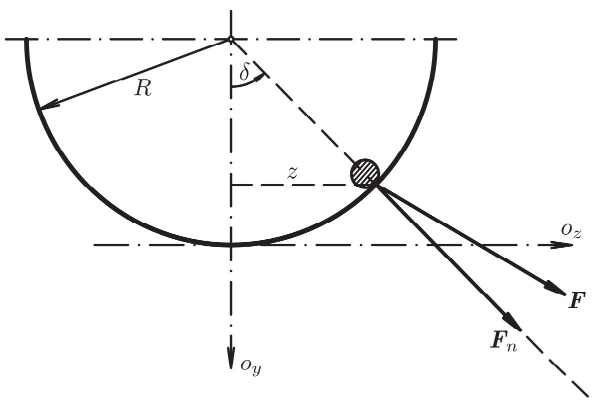

Fig. 2 Forces influencing a particle that is moving at the top chute

In the resulting kinetic equation the force denoted ***F*** is a sum of forces $\mathbf{F}_g$, $\mathbf{F}_r$ a $\mathbf{F}_C$. The kinetic equation before the particle impacts the chute is

$$m \cdot \frac{d^2\mathbf{p}}{dt^2} = \mathbf{F} \quad ,$$

where

$$\mathbf{F} = \mathbf{F}_g + \mathbf{F}_r + \mathbf{F}_C \quad .$$

After the particle impacts the chute the kinetic equation modifies as

$$m \cdot \frac{d^2\mathbf{p}}{dt^2} = \mathbf{F} + \mathbf{F}_n + \mathbf{F}_t \quad ,$$

where

$$\mathbf{F}_g = m \cdot \mathbf{g} \quad ,$$

$$\mathbf{F}_r = -m \cdot (\boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{p})) \quad ,$$

the magnitude of mentioned force is $F_r = m \cdot r \cdot \omega^2$, where *r* is a distance of the particle from the axis of the rotation,

$$\mathbf{F}_C = -2 \cdot m \cdot \left(\boldsymbol{\omega} \times \frac{d\mathbf{p}}{dt} \right) \quad ,$$

$$\mathbf{F}_n = -\mathbf{n} \cdot (\mathbf{n} \cdot \mathbf{F}) \quad ,$$

$$\mathbf{F}_t = -\frac{\frac{d\mathbf{p}}{dt}}{\left| \frac{d\mathbf{p}}{dt} \right|} \cdot \eta \cdot \mathbf{F}_n \quad .$$

The kinetic equation of a particle at the chute can be also written in following form:

$$m \cdot \frac{d^2\mathbf{p}}{dt^2} = \mathbf{F} - \mathbf{n} \cdot (\mathbf{n} \cdot \mathbf{F}) + \mathbf{F}_t \quad .$$

The above mentioned kinetic equation was applied to the chute of semicircular sectional area (see **Fig. 2**) that's equation in the coordinate system of chute is

$$y = -R + \sqrt{R^2 - z^2} \quad .$$

Trajectories of a particle that impacts the chute centrally (along the axis of the top) are shown in **Fig. 3**. The calculations were executed for two various frequencies of the chute rotation and for three angles of the chute inclination. Because the motion of a particle at the chute is influenced by the Coriolis force the direction in which the particle leaves the chute tip could be significantly different from the direction of the chute. This difference could boldly increase especially in occurrence when the particle does not impact the chute centrally (falling from the not centrally situated stack). In such situation simpler mechanistic models where the particle is assumed to move only in the direction of the chute represent unacceptable simplification to calculate the following downfall of the particle (the direction of the velocity vector determines the falling plane, among other things).

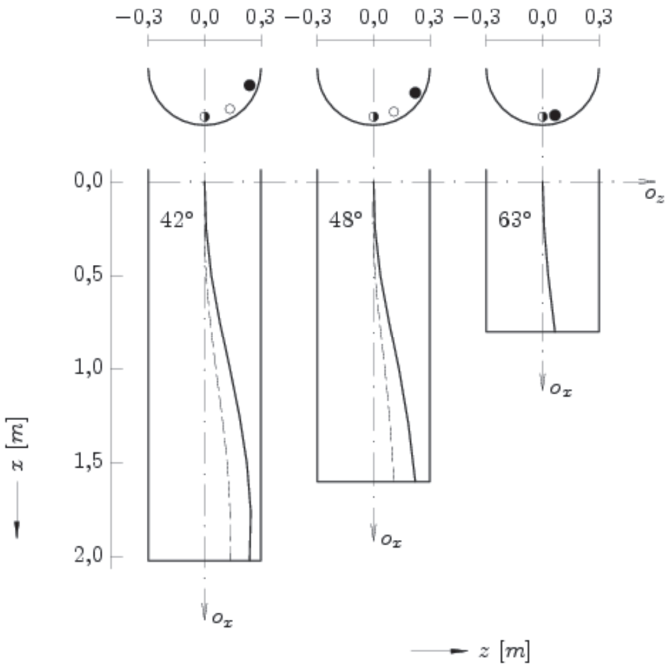

Fig. 3 Visualization of the motion of the particle at the top chute

Concrete and complete data of resulting burden distribution cannot be obtained only by using a single mathematical model of the motion of burden materials at the top chute. However, the model enables to study how individual geometrical and control parameters of the chute influence the burden distribution. Information acquired by mathematical modeling can be also advantageously used to optimize the expensive measuring for the top with new parameters.

CONCLUSION

Presented mathematical model describe only a part of motion of burden materials in a bell-less blast furnace top. Results of calculation considerably depend on initial data and act only as input data for following phases of the motion. However, with the help of the model a number of worthwhile results that cannot be produced by models that do not imply the Coriolis force were established. The model was successfully used to consider how the active length of the chute influence the burden distribution and to predict the aftereffect if a particle would not impact the top chute centrally.

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