THEORETICAL ANALYSIS OF THE EFFECT OF CORIOLIS FORCE ON THE TRAJECTORY OF BURDEN FLOW FOR BELL-LESS TOP BF[1]

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Abstract

The trajectory and landing point of burden flow is determined by forced state. Based on comprehensive analysis of burden state forced in rotary chute, this paper presents a mathematical model of burden's slippage process in rotary chute, and the related analysis are completed, mainly investigating the effect of Coriolis force (CF) and charge system on trajectory and landing point of burden flow. The results show that the velocity of burden departing from rotary chute decreases under the CF, and the landing point of burden trends the center of BF; the CF has observably effect with increase in length, angle of chute and the stock line.

Key words: Coriolis force; Trajectory of burden flow; Bell-less top; Blast furnace.

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1 INTRODUCTION

The burden distribution in the upper of blast furnace (BF) exerts strong influence on heat transfer, chemical phenomena, pressure loss in lumpy zone and even the shape-position of cohesive zone.[1-3] Therefore, both the smooth operation and low fuel ratio of blast furnace must, to some extent, depend on the reasonable burden distribution at the throat. In order to improve the performance of blast furnace, reasonable burden distribution can be achieved through controlling fall-point of burden and rational charging operation for bell-less top BF.[4] Therefore, the study on the fall-point of burden of sinter or pellet and coke has significant value for the control of burden distribution and improvement in the performance of BF.

As for the charging process, it probably includes three steps as follows, the descending in the vertical chute, slippage in the rotating chute and the movement in the free zone. The changes in every step can have effect on the burden trajectory and the fall-point of burden. In some published papers,[5-8] the trajectory of burden flow have been presented, and drag force of gas also been discussed. Nevertheless, considering the rotating chute with the circumferential velocity, thus particle in the chute will be effected by CF in the rotating chute and lead the fall-point of burden changed. In this work, the effect of CF on the trajectory of burden will be discussed, and the differences of burden distribution with or without CF will also researched.

In this paper, based on the forced state of particle in the rotating chute, a kinematical model will be built. Then, some theoretical analysis will be finished, such as the velocity that the particles depart from the rotating chute and the fall-point. Therefore, this work can afford some basic information and technology support for the improvement of charging process and the control of reasonable burden distribution.

2 KINEMATICAL MODEL

2.1 Coriolis Force

In the earth's north (south) hemisphere, when some objects goes along longitude, it's track will be affected by CF. Further more, the direction of motion will always trend to the right (left) side. The phenomenon is discovered by G. Coriolis who is engineer and scientist in France in 1835.[9] The CF will play a role on the particles in the rotary motion. During charging operation, the chute will keep the rotary state at the top of blast furnace. Therefore, when burden particles glide in the rotating chute, the CF will affect their motion. The CF can be expressed by (Formula 1).

$$\vec{F}_c = 2m\vec{v} \times \vec{\omega} \qquad \text{Formula 1}$$

2.2 Analysis of Forced State

The particles strike the rotating chute with the velocity （V_1） after they get to the end of the vertical chute. The direction and value of velocity will be changed, and the initial velocity （V_2 ）can be expressed as follows:

$$v_2 = K \times v_1 \cos\alpha \qquad \text{Formula 2}$$

About the particles in the rotating chute, their forced state is shown in Figure 1.

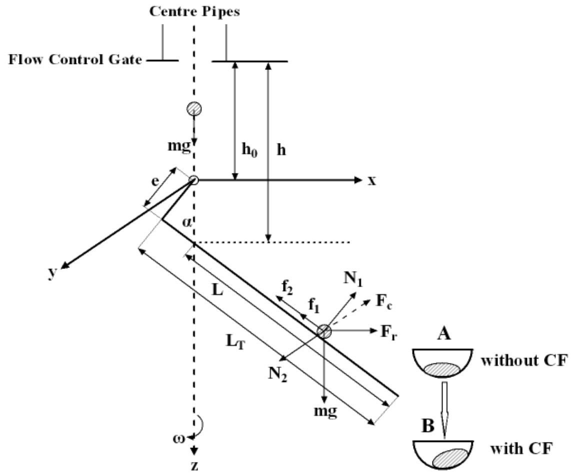

Figure 1 The sketch of particle's forced state in the rotating chute

The parameters in Figure 1 are as follows: 'h_0' is the height of vertical chute, 'h' is the distance between the bottom of vertical chute and surface of rotating chute, 'α' is the tilting angle, 'e' is the depth of rotating chute, 'L_T' is the total length of rotating chute, 'L' is the effectual length of rotating chute, 'ω' is the rotating velocity of chute.

$$N_2 = 4m\pi\omega \times v\sin\alpha \qquad \text{Formula 3}$$

From Figure 1, the particles' motion of is affected by several kinds of force. Such as 'mg' is gravity, 'N_1' and 'N_2' (Formula 3) is lateral pressure, 'f_1' and 'f_2' is the friction force, 'F_c' is CF which is equal to 'N_2' in value, but the direction is reverse, 'F_r' is centrifugal force. Without considering CF, the cross section of burden in rotating chute, which is shown by Figure 1(A), is similar with ellipse. However, with the CF, the shape of cross section is changed (Figure 1(B)).

2.3 Kinematical Model

Based on the analysis of forced state and Newton's law, the movement equation of particles in rotating chute can be expressed by Formula 4.

$$\begin{cases} v\dfrac{dv}{dl} = C_0 + C_1 \times l + C_2 \times v \\ C_0 = g(\cos\alpha - \mu\sin\alpha) \\ C_1 = 4\pi^2\omega^2\sin\alpha(\sin a + \mu\cos\alpha) \\ C_2 = -4\pi\omega\mu\sin\alpha \end{cases} \qquad \text{Formula 4}$$

'C_0', 'C_1' and 'C_2' is the constant, which are related to the operation parameters and the dimensions of rotating chute. When CF is not considered, the value of variable C_2 is 0, as is a special case of the particles' motion in the rotating chute. The classic fourth-order Runge-Kutta method will be used to obtain numerical solution of Formula 4 through the computer program.

The velocity of particles, which depart from rotating chute, can be decomposed in x, y and z direction of the three-velocity that is expressed by Formula 5.

$$\begin{cases} v_{3x}^{0} = v_3 \times \sin\alpha \\ v_{3y}^{0} = 2\pi\omega \times L\sin\alpha \\ v_{3z}^{0} = v_3 \times \cos\alpha \end{cases} \qquad \text{Formula 5}$$

3 RELEVANT PARAMETERS FOR THEORETICAL ANALYSIS

In this paper, the coke will be considered to set an example for theoretical analysis, such as the effect of CF on the trajectory and landing point of burden. Properties of coke are listed in Table 1, and some operating parameters and equipment parameters are listed in Table 2.

Table 1 Relevant property of coke

	Apparent density	Shape factor	Mean size
Coke	990 kg·m^{-3}	0.72	53 mm

Table 2 The operation and equipment parameters

Parameter	Value	Parameter	Value
total length of chute	4.60 m	depth of chute	0.65 m
hanging position of chute	3.20 m	rotating velocity	0.15 r·s^{-1}
stockline of zero	1.50 m	stockline	1 m
diameter of throat	10.5 m	tilting angle	38 degree
viscosity of gas	2.07×10^{-5} Pa.s	density of gas	2.12 kg·m^{-3}
velocity of gas	1.32 m.s^{-1}	coefficient of friction	0.53
depth of filler	1.50 m	width of platform	1.50 m

Hereinto, the average velocity of gas at the top of BF under well-balanced condition is considered. In the following context, the values of parameters will choose the corresponding value listed in Table 2 unless special explanation has been given.

4 RESULTS AND DISCUSSION

Based on the kinematical model, the velocity of particles in rotating chute can be obtained. Additionally, the velocity of particles that depart from the rotating chute is also the initial velocity of particles that rush into free zone. With the effect of CF, the velocity of particles that depart from the rotating chute and stackpoint of mainstream will change. The trajectory of burden flow is not only affected by forced state but also determined by operation parameters and equipment parameters, such as total length of rotary chute、tilting angle、stock line level etc.

4.1 The Effect of CF and Total Length of Chute on the Coke Velocity

Under the CF, the relationship between total length of chute and velocity of coke departing from the chute is shown in Figure 2. The abscissa is the total length of chute; ordinate (left) is the coke velocity while the ordinate (right) is the difference under considering CF or not. The relationship between the coke velocity and the chute length is shown in Line (a) with the CF, while line (b) illustrates the relationship without the CF, and line (c) is the difference in line (a) and line (b). When the length of rotary chute is 4.6 meters, point B and A mean the downglide velocity of burdens under the CF or not respectively, and point C is the downglide speed difference between point A without CF and B with CF. Additionally, the Figures hereinafter have the similar means.

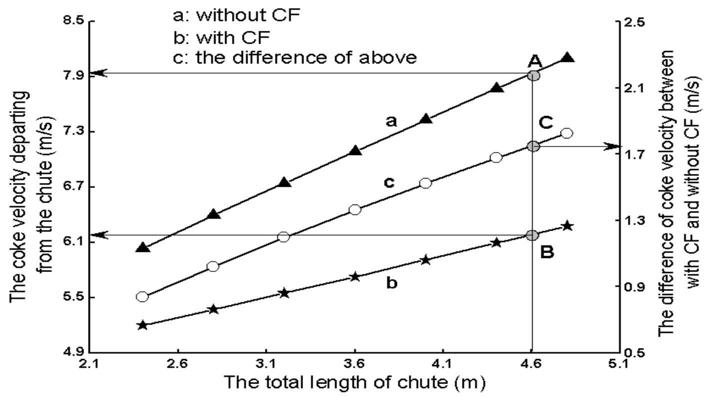

Figure 2 Relationship between total length of chute and the coke velocity departing from the chute

From Figure 2, whether the CF is considered or not, the coke velocity departing from the chute increases linearly with increase in the total length of chute. However, owing to the effect of CF, the coke velocity will to some extent decrease under the same length of chute. The difference of coke velocity whether considering the CF or not will be enlarged with increase in the total length of chute. Taking BaoSteel for example, the total length of chute is 4.6 meters; the coke velocity is 7.94 m· s^{-1} without considering CF while the coke velocity is 6.17 m· s^{-1} with CF, and the speed difference between the above two cases will reach 1.77 m· s^{-1}. Therefore, the CF should not be left out.

4.2 The Effect of CF and Tilting Angle on Outlet Velocity of Coke

Figure 3 shows the relationship between tilting angle of the chute and the coke velocity with CF. Whether the CF is considered or not, the coke velocity departing from the chute increase at beginning and then decrease with the increase of tilting angle. And the difference caused by CF will be enlarged when the tilting angle increases.

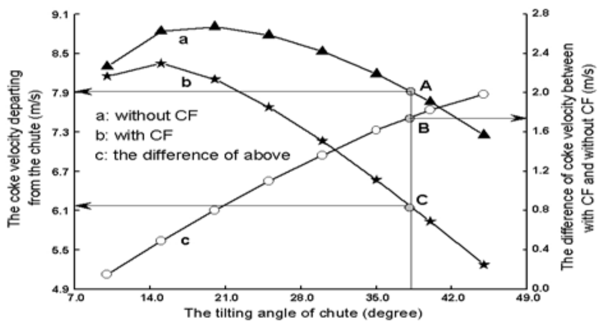

Figure 3 Relationship between tilting angle and the coke velocity with CF

From Figure 3， it can be seen that the coke velocity reach the peak at round 17 degree of tilting angle. On the one hand, the friction force will increase with the increase of tilting angle, which makes the coke velocity decrease. On the other hand, the effective length of chute will increase, which makes the coke velocity increase. (Figure 4 shows the relationship between total length of chute, tilting angle and the effective length of chute.) When tilting angle is less than 17 degree, the effective length of chute increases obviously with the increase of tilting angle, which is helpful to increase the coke velocity. However, while the tilting angle is more than 17 degree, the friction force increases obviously with the increase of tilting angle, which will make the coke velocity decrease.

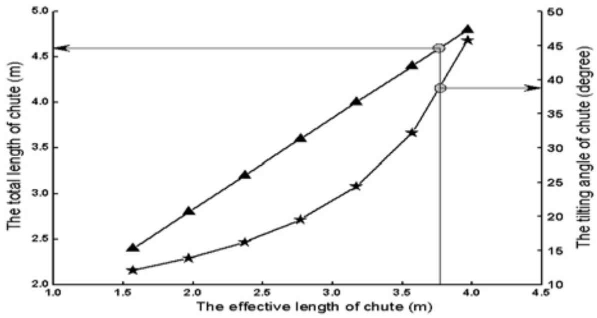

Figure 4 Relationship between total length of chute, tilting angle and the effective length of chute

4.3 The Effect of CF and Sock Line Level on Landing Point of Coke

Under the CF, the initial velocity of particles rushing into free zone will decrease to some extent during, which will make the landing point of burden change. In free zone, the gas resistance makes important effect on the particles' trajectory, especially for the small size particles. Figure 5 shows the relationship between stockline levels and landing point with CF.

Whether the effect of CF is considered or not, the landing point of particles will linearly increase with the increase in the stock line level. The effect of CF is to make the landing point of particles trend to the center of the throat, and this difference will be enlarged when the stockline level increases. Taking BaoSteel for example, the stockline level is 1.0m. Without CF, the landing point of particles is 4.254 m, however, the landing point of particles is 4.102m with the CF. That is to say, there is the difference of 0.152m.

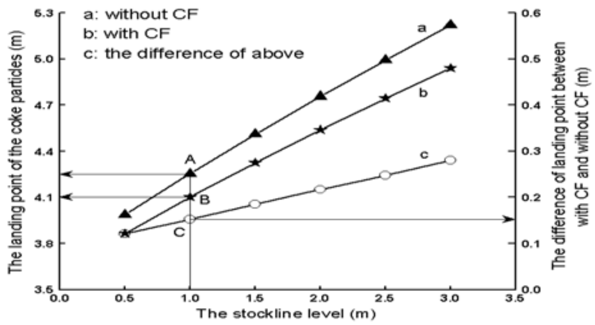

Figure 5 Relationship between stockline level and landing point of coke

4.4 The Effect of CF and Tilting Angle on Landing Point of Coke

Figure 6 shows the relationship between tilting angle of the chute and landing point of the particles with CF. Whether the effect of CF is considered or not, the landing point of the particles increases with increase in the tilting angle of the chute.

The effect of CF is also to make the landing point of the particles trend to the center of the throat, and this difference will be enlarged when the tilting angle increases. Taking BaoSteel for example, the tilting angle is 41 degree. Without CF, the landing point of the particles is 4.696 m, however the landing point of the particles is 4.488m with CF. In another words, the difference is up to 0.208m which is almost more than the broad of “half-ring” around the wall.

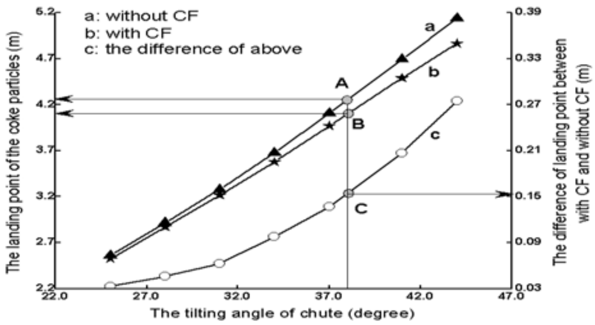

Figure 6 Relationship between tilting angle and landing point of the particles

5 CONCLUSIONS

(1) With regard to bell-less top, it is necessary to consider the effect of CF on the trajectory of burden flow and landing point of the particles.
(2) The charging system and forced state of the particles have important effect on the trajectory of burden flow and landing point of main stream directly. Thereinto, the forced state of burden particles not only includes the drag force of gas in free zone but also includes the CF in rotating chute.
(3) With the effect of CF, the burden’s velocity departing from the chute decreases and the landing point trend to the center of BF.
(4) The effect of CF is obvious as the total length of chute、stockline level and tilting angle are larger.

Nomenclature

$\vec{F}_c$ (N_2): coriolis force, (N)

$\vec{\omega}$: rotating velocity of chute, (rad/s)

m : the weight of burden particles, (kg)

$\vec{v}$: the velocity of particles relative to chute (m/s)

K : coefficient of reducing velocity, (-)

α : tilting angle of chute, (degree)

μ : coefficient of friction, (-)

C_0、C_1、C_2: the constants determined by equation

l : the effective length of chute, (m)

v_3 : the velocity of particles that depart from the rotating chute, (m/s)

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