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RESEARCH OF LATERAL FORCE OF PIPE CONVEYOR BELT'S VERTICAL TRANSPORT SECTION

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Abstract: *In order to release the lateral force of pipe conveyor belt in vertical transportation, the thesis had a study of the lateral force of the conveyor belt. By making use of Janssen Principles and fractal theory, based on reasonable simplification, the author established a mathematical model of the lateral force in vertical transportation, and with the research foundation of the pipe belt conveyor for underground transportation, through solution analysis, the author found out that the change of material diameter would lead to nonlinear variation of the lateral force of the conveyor belt. Under the circumstances of different material diameter, discrete element method was adopted to simulate the lateral force of the conveyor belt, thus working out the distribution curve chart of the lateral force. To verify the reliability of the theory, the author built an experimental platform for pipe conveyor belt in vertical transportation, and experimented with five groups of materials in different diameter, working out the strain of lateral force of the characteristic conveyor belt; by comparing the theoretical result, the simulation result and the experimental result, it showed that the solution to relieving lateral force through optimization selection of material diameter put forward in this thesis was reasonable and effective. It provides theoretical reference for the design of pipe belt conveyor.*

Key words: *pipe belt conveyor, vertical transport section, lateral force, discrete element simulation, experimental verification*

1. Introduction

The pipe belt conveyor is a special belt conveyor developed from the ordinary belt conveyor (Wang Ying et al.,2003). Compared with the ordinary belt conveyor, the pipe belt conveyor is of better usability, including features of smaller installation space, closeness and environmental protection, space curve and high-inclination conveying (Greg, 2010; Will et al.,2011). Particularly, the Chinese-type pipe belt conveyor improved by professor Zhang Yue (Xiao, 1997), a famous domestic expert in belt conveyors adopts soft conveyor belts to increase the encapsulation and chucking power, which greatly promotes the dip angle in transportation even in vertical transportation, and it has realized industrialized application in many places of China. As to the vertical transportation of the pipe belt conveyor, inside the conveyor belt, it is full of bulk material particles, and under the effect of multiple forces including gravity, friction, material lateral force, tension and roller positive force, its force condition is more complex compared with normal transportation. Particularly, the over large lateral force of materials will reduce the service life of the conveyor belt, which will greatly increase the cost of using pipe belt conveyors in actual practice(Xie et al., 2007). Meanwhile, the assumption that the computing method of the lateral force of the conveyor belt comes from the lateral force of bulk material in the static silo still hasn't been universally received in the academic circle, which also has become the research topic of many domestic and foreign scholars. Professors Molnár Vieroslav (2014) made use of the experimental platform for the comprehensive testing of the transition section in the pipe belt conveyor, and through data regression analysis, worked out the formula of the conveyor belt's lateral force and the roller's arrangement distance. Professor Zamiralova Maria E and Lodewijks Gabriel (2014) jointly designed a professional testing device for the pipe belt conveyor, which could carry out real-time testing of the static and dynamic mechanical characteristics of the pipe belt conveyor; Scholars from Netherlands (2013) established the finite element model of the pipe conveyor belt and conducted simulation, and through the comparative analysis between the simulation result and the measured result, the static characteristics of the pipe conveyor belt was worked out. In addition, the scholars of Australia (2001), Poland (2000), Spain (2007), Malaysia (2013) and other countries have carried out thorough researches on the pipe belt conveyor. In the 90s, the author of this paper studied the design of the tension transition section of the circular pipe belt conveyor; other domestic scholars like Sun Kewen (1996) and Yang Houhua (2006)also did research on the tension of the conveyor belt in the circular pipe belt conveyor. Based on the problems above, as the theory of vertical lifting appeared relatively late, most designs on the vertical transportation section of the pipe belt conveyor are mainly based on experience so far, and there are only limited literature reports on relevant researches. Therefore, to make sure of the reliability of the vertical transportation, it is necessary to have a deep research on it.

2. Mathematical model

The author of this paper and Kasen Heavy Industry Co., Ltd collaborated the first underground pipe belt conveyor in 2012, which obtained industry first coal mine safety (MA) certificate and successfully applied in Xieqiao coal mine of huainan mining group working face along the empty left lane assignments. It laid a solid foundation for the study of the theory of the pipe belt conveyor and practical application.

Fig. 1. Chinese first coal mine underground pipe belt conveyor

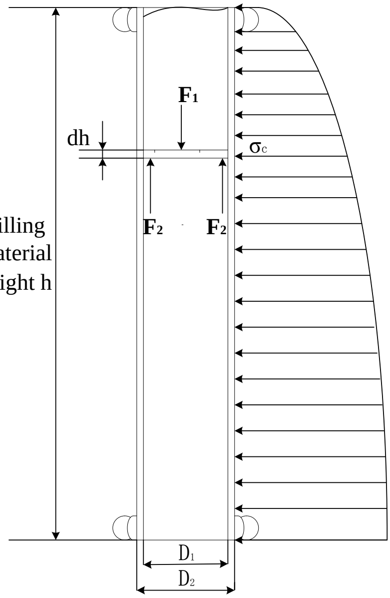

Fig. 2. Pipe belt conveyor lateral stress distribution model

When the pipe belt conveyor is transporting materials vertically, materials in the lower layer tend to go down under the effect of gravity of those in the upper layer. By taking a layer of materials with infinitely small *dh* as the unit to analyze, the direction of the friction F_1 among material particles is downward, while the friction F_2 between the pipe conveyor belt and materials acts on the materials, whose direction is upward. Thus, the differential formula of the vertical force acting on *dh* of the unit is as follow:

$$\begin{cases} \sigma \cdot \dfrac{\pi D_1^2}{4} + \rho g dh \cdot \dfrac{\pi D_1^2}{4} + F_1 = (\sigma + d\sigma) \cdot \dfrac{\pi D_1^2}{4} + F_2 \\ F_1 = \sigma_c \cdot dh \cdot f_1 L_1 \\ F_2 = \sigma_c \cdot dh \cdot f_2 L_2 \end{cases} \tag{1}$$

In the formula, σ is the upper materials' force stress towards *dh* of the unit, σ_c is the lateral force stress the unit receives, ρ is the density of materials, D_1 is the internal diameter of the pipe, L_1 is the internal perimeter, $L_1 = \pi D_1$. The external diameter is D_2 and

the outer perimeter is L_2, $L_2=\pi D_2$. The friction coefficient among materials is f_1, and the friction coefficient between the materials and the conveyor belt is f_2.
According to Janssen Principle and combined with the actual working condition of the pipe belt conveyor, thus:

$$\sigma = \frac{\sigma_c}{n^{'}} \qquad (2)$$

There into,

$$n^{'} = \frac{1}{1+2f_2^{\,2}+2\sqrt{1+f_2^{\,2}}\left(f_2+\sqrt{f_2^{\,2}-f_1^{\,2}}\right)}$$

Substitute (2) into (1), thus :

$$\begin{aligned}&\sigma_c\cdot\frac{\pi D_1^2}{4n^{'}}+\rho g dh\cdot\frac{\pi D_1^2}{4}=\\&=\left(\sigma_c+d\sigma_c\right)\cdot\frac{\pi D_1^2}{4n^{'}}+\sigma_c\cdot dh\left(f_2\cdot L_2-f_1\cdot L_1\right)\end{aligned} \qquad (3)$$

As the bulk materials are distributed inside the pipe conveyor belt layer by layer, the materials in the lower layer will go down under the mass action of the upper layer, so in order to simplify the calculation of the force in every layer, "collapse coefficient μ" is introduced (Steacy et al., 1991):

$$\mu = \frac{1}{\boldsymbol{a}_v h}\left(1-\frac{1}{e^{\boldsymbol{a}_v h}}\right) \qquad (4)$$

In the formula, $\boldsymbol{a}_v$ is the vertical acceleration of materials, and h is the height of the filling materials. If $\boldsymbol{a}_v$ is unknown, we can consider using the dynamic coefficient $k_{\boldsymbol{g}}$ (Mandelbrot, 1982) to modify, thus:

$$k_g = 1+\frac{\boldsymbol{a}_v}{g}$$

In the formula, g is the free falling body acceleration.
Substitute (4) into (1), and it changes into:

$$dh = \frac{\mu d\sigma_c}{\rho g n^{'} - \dfrac{4\left(f_2\cdot L_2-f_1\cdot L_1\right)\sigma_c n^{'}}{\pi D_1^2}} \qquad (5)$$

Make $\dfrac{4\left(f_2\cdot L_2-f_1\cdot L_1\right)n^{'}}{\pi D_1^2}=a^{'}$, and substitute it into (5), thus:

$$dh = \frac{\mu d\sigma_c}{\rho g n^{'} - a^{'}\sigma_c} \qquad (6)$$

Settle formula (6), thus:

$$\sigma_c = \frac{1}{\mu}\int\left(\rho g n^{'} - a^{'}\sigma_c\right)dh$$

That is:

$$\sigma_c = \frac{\rho g n^{'}}{\mu a^{'}}\left(1-\frac{1}{e^{a^{'}h}}\right) \qquad (7)$$

From formula (7), it can be seen that the trace characteristics of the lateral force is shown in graph 1, and in formula (7), with the increase of the filling height h, $e^{1/a'h}$ tends to be zero. So the lateral force tends to be the limiting value, which is:

$$\sigma_c = \frac{\rho g n^{'}}{\mu a^{'}}$$

Substitute $a^{'} = \dfrac{4\left(f_2\cdot L_2-f_1\cdot L_1\right)n^{'}}{\pi D_1^2}$ into formula (6), thus:

$$\sigma_c = \frac{\rho g \pi D_1^2}{4\mu\left(f_2 L_2 - f_1 L_1\right)} \qquad (8)$$

Fractal dimension is an important principle in fractal theory, which is defined as : $R(x)$ is a nonvoid subset of d-euclid space (X, d), and as to the set $A\in R(x)$, it can be covered by finite ($N(A, r)$) closed sets whose radius is $r>0$, so:

$$Q = \lim_{r\to 0}\left\{ln\left[N\left(A,r\right)\right]/ln\left(1/r\right)\right\}$$

Then Q is the fractal dimension of set A.
As to the fractal model of raw coal materials, in Fig. 3, the block section stands for the solid parts of raw coal, while the white part stands for the gap

distribution of particles. Taking a cube particle in cell size, assuming it breaks into particles with 1/2 of its size, if the particle is a three-dimentional Euclidean block, after breaking, it will form 8 secondary particles. As the material particles are fractal patches and there exist cracks and defects, after breaking, it will not form 8 secondary smaller blocks. However, the total amount of the number of cracks and secondary material particles remains the same; the fractal patches with 1/2 of its size will break according to the rules above.

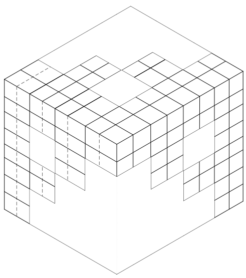

Fig. 3. Fractal particle crushing model

As to the fractal distribution, the number of particles *N* and its size *d* meets the following relation(Wang Jun et al.,2009):

$N(d)=d^{-Q}$

In the formula, *Q* is the fractal dimension of the raw coal materials after breaking, which ranges from 2.0 to 3.0(CHENG Chang-bing,2006). Under normal circumstances, assuming the initial diameter of the raw coal particles is d_1, and the number of the secondary particles whose grain size is d_1/b is b_w, *w* is conventional Euclidean dimension, so the secondary particles break according to the same rules above. After repeated breaking for *i* times, the grain size of the particles after breaking is $d_i= d_1/b_{i-1}$, and the number of particles is expressed as $N(b_i)=(pb_w)_i=(b_i)(w+\ln P/\ln b)$
The fractal dimension of the particles after breaking is $Q=w+\ln P/\ln b$.
To approximately estimate the volume of the materials, assuming the particles are sphere, the total volume of the materials is:

$$V = N(d)\cdot\frac{4\pi}{3}\cdot\left(\frac{d}{2}\right)^3 \tag{9}$$

Assuming the humidity of the materials is *W*, the total volume of materials inside the pipe conveyor belt in vertical lifting transportation is:

$$V = \frac{\pi D_1^2 h}{4}(1-W) \tag{10}$$

Substitute (10) into (9), so:

$$\frac{\pi D_1^2}{4} = \frac{d^{3-Q}}{6(1-W)h} \tag{11}$$

Substitute (11) into (8), so :

$$\sigma_c = \frac{(k_g-1)g}{\left(1-\frac{1}{e^{(k_g-1)gh}}\right)}\cdot\frac{\rho g d^{3-Q}}{6(1-W)(f_2L_2-f_1L_1)} \tag{12}$$

Formula (12) is the analytical form of the lateral force of the pipe conveyor in vertical transportation. The lateral force of the conveyor belt in vertical transportation σ_c is related to factors like material diameter *d*, fractal dimension *Q* , filling material height *h*, material density *ρ*, humidity *W*, conveyor belt's internal and outer perimeters L_1、L_2. In this thesis, based on the pipe belt conveyor for underground transportation, aiming at material diameter, the author did a research on the lateral force of the pipe belt conveyor in vertical transportation from the factors above. From formula (12), we can see that the material diameter plays a crucial role in affecting the lateral force of pipe conveyor belt in vertical transportation: relative to the material diameter, the change of lateral force is nonlinear. As the material diameter increases, the lateral force also increases, while with the gradual increase of material diameter, the increment of lateral force decreases gradually.

3. Simulation analysis

3.1. Parameter setting of discrete element model

By making use of Solidworks, the author establishes a 3D model of the conveyor belt in vertical transportation, maps the complete machine model in the modern discrete element model software EDEM, and then sets the global parameter model and establishes particle factory, after which the similar is done. Finally a 3D model with the following parameters is established: pipe diameter 250mm, hexagon roller set distance 1000mm, filling material height 1000mm, roller diameter 89.1mm, belt speed 2.0m/s, rated delivery value 600t/h. In order to estimate the size of material particles, its shape is set as sphere. Setting the simulation area is the internal pipe conveyor belt, and the basic flow parameters are: the filling material particles are 12000 spherical particles, and the generation rate of the particle factory is 2700 particles/s.

To make sure of the stability of the iterative computations of particle system, in actual computation, proper time step should be selected according to the acute degree of particle movement. The Raleigh time step is worked out according to the radius of 50mm, but according to this simulation, selecting 30% of the Raleigh time step of the particle with minimum radius as the time step, i.e. 3e-04s; the conveyor belt model adopts Moving-Plane model, which is used to simulate the uniform linear motion of the conveyor belt.

Table 1. Contact properties of the materials

Material	Poisson's ratio	Shear modulus (GPa)	Density (t/m^3)
coal	0.28	1.98	1.2
Belt (ruby)	0.47	0.00267	0.9

Table 2. Contact properties of the materials

Material	Recovery coefficient	Static friction coefficient	Rolling friction coefficient
coal-coal	0.5	0.6	0.05
coal-belt (ruby)	0.45	0.5	0.05

3.2. Discrete element simulation

In vertical transportation, the pipe belt conveyor will produce lateral force to the conveyor belt, and the lateral force is one of the most important problems in vertical transportation of materials of the pipe belt conveyor.

Before simulation, there is no material inside the conveyor belt. Materials are produced in the particle factory, which fall into the conveyor belt and are accelerated to certain belt speed. After operation for a period, the parameter data under stable operation state are measured, and EDEM simulation can be ended. In Fig. 4, the frame of the blue column is the simulated measurement area of EDEM.

Fig. 4. The lateral force measurement area of EDEM simulation

In discrete unit simulation, the force area of the conveyor belt in vertical transportation is measured. Under the premise of maintaining the invariable rated delivery value of the materials, by changing the feeding rate of the particle factory, keep the volume at 600t/h. Materials with diameter of 10mm, 20mm, 30mm, 40mm and 50mm are used to do computer simulation, and in the simulation process, the curve graph of different force of the conveyor belt ranging from 0s to 5s is shown in fig. 5.

Table 3. Test data table

Material diameter (mm)	Lateral force average (N)	Materials under different diameter of the lateral force average increment Δ(N)
10	31.5	/
20	44.9	13.4
30	57.2	12.3
40	64.3	7.1
50	70.1	5.8

From fig.5 and table 3, the lateral force of the pipe conveyor belt in vertical transportation is connected with the material diameter. When the material diameter is 10mm, the average value of its lateral force on the conveyor belt is 31.5N, and when the diameter is 20mm, this value is 44.9N. It shows that the increase of material diameter will lead to the increase of the lateral force; when the material diameter increases from 10mm to 20mm, 30mm, 40mm and 50mm, the average value of the lateral force is successively 31.5N, 44.9 N, 57.2 N, 64.3 N and 70.1 N.

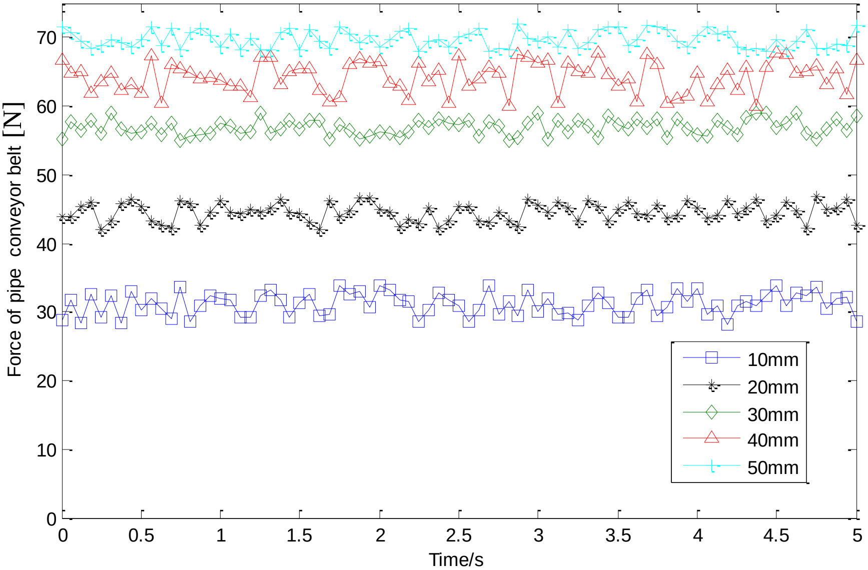

Fig. 5. Simulation graph of the pipe conveyor belt force under different particle sizes

That is, the average value of the lateral force on the conveyor belt increases with the increase of the material diameter; and the increment of the average value is successively 13.4N, 12.3N, 7.1N and 5.8N, presenting a tendency of gradual decrease. This is consistent with the result analyzed in the theoretical formula.

4. Experimental verification

4.1. Building an experimental platform

This experiment is built on the independently developed experimental platform of the pipe conveyor belt for vertical transport. This experimental platform is composed of hexagon roller sets and ordinary conveyor belts, as it is shown in fig. 6. Relevant parameters are as follows: the pipe diameter of the pipe conveyor belt is 250mm, the frame size of the pipe belt conveyor (length×width × height) is 2000×620×620mm, the frame material is 45 steel, the roller size is φ89×280mm, the roller set distance is 1000mm, and feeding material is coal, whose density is 1200kg/m^3.

The strain signal of the conveyor belt in the pipe belt conveyor for vertical transportation is collected through the strain gage and data acquisition card fixed near the side of a hexagon roller in advance and to eliminate the influence of the strain gage's installation position on the experiment, the strain gage is fixed to the position 500mm away from the side of the roller set for repeated experiments.

Fig. 6. Test device

In the experiment process, materials of five different diameters are respectively fed to experiment including diameter of 10mm, 20mm, 30mm, 40mm and 50mm. Then through the data acquisition card and the computer, the strain signal of the lateral force of the conveyor belt in the characteristic pipe belt conveyor, and combined with the signal analysis software, it carries out relevant data processing. The experiment's principle scheme is shown in Fig. 7.

4.2. Experiment results and analysis

To verify the viewpoint put forward in this thesis, through experiment design, materials with diameter of 10mm, 20mm, 30mm, 40mm and 50mm are fed into the conveyor belt of the pipe conveyor according to different filling rates, thus acquiring the strain signal of the conveyor belt of the pipe belt conveyor, and then relevant study and analysis is done on the data. LabVIEW software is used to design a multi-channel data collection loop. When measuring with LabVIEW, DAQ assistant is set as follows: a quarter of bridge road test is adopted, whose loop power voltage is 5V, strain gage is 120 Ω high-precision resistance strain gage. To prevent the inference of other signals, the cut-off frequency of the filter is set as 20 Hz. Average the data and map the collected strain value, and finally get fig. 8.

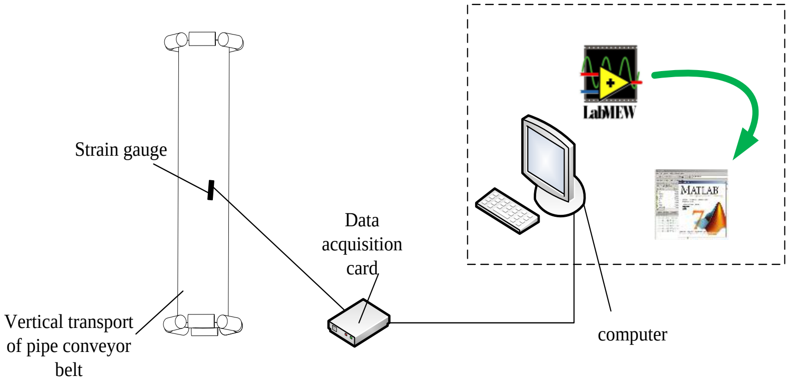

Fig. 7. Experiment scheme figure

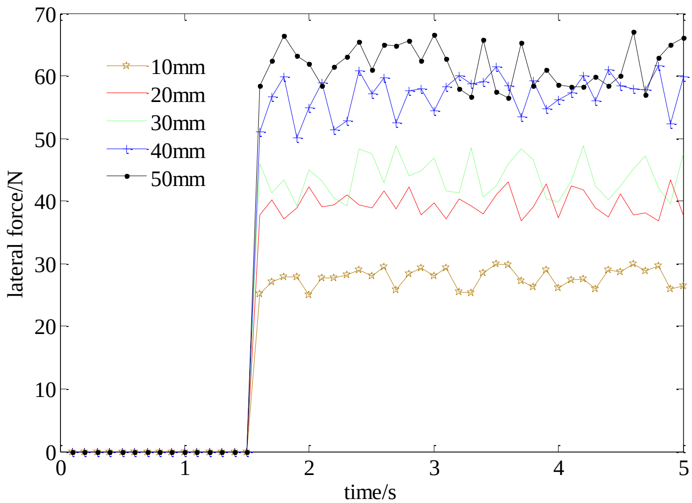

Fig. 8. The conveyor belt strain scatters under different particle sizes

Table 4. Simulation and experiment contrast on different diameters

Material diameter(mm)	Simulation value(N)	Experiment value(N)	Relative error
10	31.5	29.3	7.0%
20	44.9	40.2	10.5%
30	57.2	49.7	13.1%
40	64.3	58.6	8.8%
50	70.1	65.8	6.1%

Fig. 8 offers the lateral force chart of the pipe conveyor belt for vertical transportation under different diameter including 10mm, 20mm, 30mm, 40mm and 50mm. from the graph we can see that with different material diameter, when the other parameters influencing the lateral force of the conveyor belt are the same, there exists difference in the lateral force value of the conveyor belt, while the fluctuation effects are similar. Based on Table 4, we can know that simulation value and experiment value of the lateral force which vary with changes in material diameters have a basically identical variation tendency. The maximum error for simulations and tests is 13.1%; the lateral force value obtained through simulation is slightly larger than the experiment one. Combined with the experiment result, we can see these phenomena show that under different conditions of diameter, the material's methods of extruding the pipe conveyor belt are the same, while the lateral forces change. The main cause is that there exists gap among the materials, and those with smaller diameter are likely to fill some gap because of its smaller size. On the contrary, with the increase of the material diameter, not only will the gap among materials increase, but also there is unlikely to be filling gap of materials in small diameter. Therefore, under the same volume, it will produce larger lateral force on the pipe conveyor belt.

5. Conclusions

(1) The thesis puts forward a 3D dynamic simple model of the conveyor belt in pipe belt conveyor for vertical transportation. Based on reasonable assumption, a mathematical model of the lateral force of the conveyor is built. Aiming at the pipe belt conveyor for underground usage, the author analyzes the lateral force of the conveyor belt in vertical transportation under the circumstances of different material diameter;

(2) By having a simulation analysis of the lateral force of the conveyor belt in the pipe belt conveyor for vertical transportation, the result shows that under the action of different material diameter, there is a non-linear change in the value of the lateral force. The lateral force increases with the increase of the material diameter while the increment decreases gradually. It analyzes the relation between lateral force and material diameter more accurately, which is consistent with the theoretical analysis result;

(3) Through experiment design, it finds out the lateral force variation diagram of materials with different diameter towards the pipe conveyor belt under the circumstance of vertical transportation. The experimental result shows that the lateral force of the conveyor produces nonlinear change, which also verifies the result in simulation analysis and theoretical analysis.

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