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Research Article

Analysis and Experimental Study on Pressure Characteristics of Supporting Roller Group of Pipe Belt Conveyor

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Aiming at the problem in measuring the nonuniformly distributed pressure generated by the pipe belt conveyor when conveying raw coals, a hexagonal adjustable pressure measuring device for the idler group is proposed. The dynamic model of the pipe belt conveyor clamping-type roller group is established. In order to simplify the calculation process of mechanical analysis, the modal analysis is carried out to determine the factors which will influence the pressure. The pipe diameter and filling rate are selected as the key control factors by the sensitive analysis of pressure of the pipe belt conveyor clamping type roller group. An adjustable diameter-type supporting roller group experiment device is self-designed, and the dynamic pressure change of the roller group and each roller pressure are tested. The results show that the average error between the simulated and tested values of the pressure of the idler group at different filling rates is 7.3%; the theoretical and simulated values of the pressure of the idler group are in good agreement with the experimental values. The study provides a theoretical basis and experimental reference for the design and application of pipe belt conveyors.

1. Introduction

Nowadays, countries around the world are shifting towards a development model highlighted by green ecology and low carbon [1]. However, the environmental pollution, which is caused by a large amount of dust and scattering granules generated by the bulk material transfer system during work, has raised more and more attention in the conveyor industry around the world [2]. Many countries have proposed the use of environmentally friendly pipe belt conveyors to reduce the environmental pollution from the conveying process [3, 4]. Moreover, a pipe belt conveyor has shown great development prospects [5] because it overcomes the shortcomings of the traditional belt conveyor, such as the susceptibility of generating dust and scattering granules, the vulnerability to which it is hampered by spatial restrictions, and the small turning inclination angle [6].

The conveyor belt of the pipe belt conveyor is guided by the idler [7]. Also, the flat belt passing through the roller gradually takes the shape of a pipe belt to increase the enveloping surface of the conveyor belt to the material and ensure the enclosed conveying of the material [8]. Zamiralova et al. studied the rotational resistance of the idlers of the pipe belt conveyer and reduced the resistance of the idler during the conveying process [9, 10]. The comparative analysis between the force distribution of the pipe belt conveyer under no load and that of the traditional belt conveyor was conducted, and the dynamic wear analysis of the rubber conveyor belt of the pipe belt conveyer was performed by Fedorko et al. [11, 12]. Molnár et al. presents design and verification of regression models for prediction of pipe conveyor belt contact forces on idler rolls. Several criteria have been used to verify the presented regression models [13, 14]. Lodewijks tested the rolling resistance coefficient between the rubber conveyor belt and the idlers and investigated the turning characteristics involving large inclination angle of the round belt conveyor [15, 16]. Professor Weigang Song pointed out the unreasonableness of the original shaping theory of the transition segment, proposed the circular section theory of the transition segment of the pipe belt conveyor, and provided the shaping diagram of the transition segment of the pipe belt conveyor using computer simulation [17, 18]. Based on the differential elements shaping theory, Professor Houhua Yang analyzed the mechanical behaviors of the adhesive tape in the transition segment of the pipe using a computer simulation technology, and the geometric distribution of mechanical behaviors was obtained through simulating the mechanical behaviors of the target under the influence of complex forces [19].

However, many of the above studies were just focused on the no-load conveying of the pipe belt conveyor, but the conveying of raw coal and other materials was not taken into account. In this paper, a pressure testing device for the hexagonal adjustable idlers was proposed to solve the difficulty in measuring the nonuniformly distributed pressure generated by the pipe belt conveyor when conveying raw coals. Moreover, a mechanical model of the bottom-type idlers of the pipe belt conveyor was established. Then, the sensitivity analysis on the factors influencing the pressure of the idlers was completed to reduce the workload of the mechanical analysis of the idlers. The main control factors were then found based on the weighting to be the pipe diameter and the filling rate. Finally, the conclusions of the theoretical analysis were verified through a series of simulations and tests.

2. Pressure Analysis of Idlers of Pipe Belt Conveyor

The 16.7 km pipe belt conveyor developed by the project team in 2019 has been successfully applied, as shown in Figure 1.

Figure 1: The pipe conveyor.

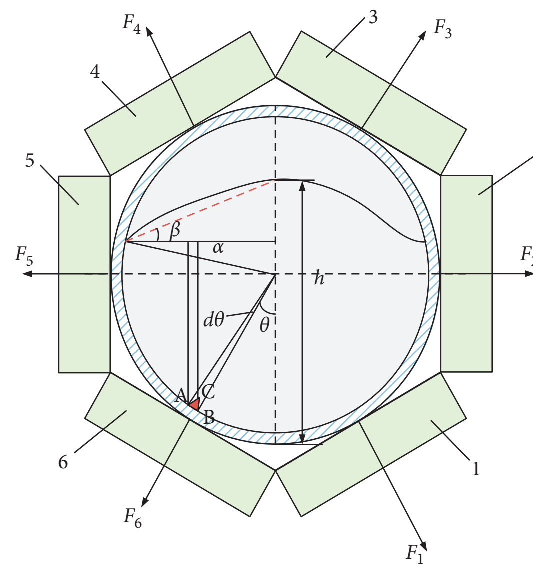

Figure 2: Clip-type bottom roller material element diagram.

2.1. Analysis of Total Pressure of Idlers. As shown in Figure 2, θ is the deflection angle of materials, α is the angle related to the material filling rate, and β is the repose angle of materials.

The conveyor belt's total pressure F_i $(i = 1, 2, \ldots, 6)$ applied on the idler is

$$F_{l1} = F_{l6} = \frac{1}{2}\rho g R^2 L \int_0^{(\pi/3)} [\cos\theta + \sin\alpha + (\cos\alpha - \sin\theta)\tan\beta] \times \left[(n_{\max} + n_{\min})\cos^2\theta + 2\sin^2\theta x\right] d\theta, \quad (1)$$

$$F_{l2} = F_{l5}\frac{\rho g R^2 L}{2}\int_{(\pi/3)}^{(2\pi/3)} [\cos\theta + \sin\alpha + (\cos\alpha - \sin\theta)\tan\beta] \times \left[(n_{\max} + n_{\min})\cos^2\theta + 2\sin^2\theta\right] d\theta, \quad (2)$$

$$F_{l3} = F_{l4} = \frac{\rho g R^2 L}{2}\int_{(2\pi/3)}^{\pi} [\cos\theta + \sin\alpha + (\cos\alpha - \sin\theta)\tan\beta] \times \left[(n_{\max} + n_{\min})\cos^2\theta + 2\sin^2\theta\right] d\theta, \quad (3)$$

$$F_{c1} = F_{c2} = F_{c3} = F_{c4} = F_{c5} = F_{c6} = \frac{\pi}{3} L \times \frac{\sqrt{3} E_b b^3}{18\left(1 - \mu_x \mu_y\right) R^2}, \quad (4)$$

$$\begin{cases} F_{g1} = F_{g6} = \dfrac{q_B}{B} \times \dfrac{\pi R L}{3}\cos\dfrac{\pi}{3}, \\ F_{g2} = F_{g5} = \dfrac{q_B}{B} \times \dfrac{\pi R L}{3}\cos\dfrac{2\pi}{3}, \\ F_{g3} = F_{g4} = \dfrac{q_B}{B} \times \dfrac{\pi R L}{3}\cos\pi, \end{cases} \quad (5)$$

$$F_i = F_{li} + F_{ci} + F_{gi}. \quad (6)$$

It can be concluded from the aforementioned equations that idlers of the pipe belt conveyor are subject to three forces, including belt lateral pressure $F_{li}(i = 1, 2, \ldots, 6)$, belt circling force $F_{ci}(i = 1, 2, \ldots, 6)$, and belt gravity force $F_{gi}(i = 1, 2, \ldots, 6)$ [20].

As can be seen in equations (1)–(6), variables related to the force of idlers are density of material transportation ρ, material filling height h, distance between idlers L, pipe radius R, elastic modulus of the conveyor belt E_b, width of the conveyor belt B, etc. The sensitivity analysis is needed to select a design variable having the greatest effect on the pressure of idlers from optimizable variables; i.e., when the variable changes slightly, the changes of the pressure of the idler groups are regarded as sensitivity [21, 22].

3. Determination of Pressure Optimization Variables of Idlers of Pipe Belt Conveyor

3.1. Sensitivity Analysis Model. In engineering design, design sensitivity is often defined as the derivative of structural response obtained by design calculation with respect to a design variable. That is, a structural response represents structural response function $F(X)$'s sensitivity to design variable x_i at a specified design point x_i:

$$S_{x_i}(X) = \frac{\partial F(X)}{\partial x_i}, \tag{7}$$

where S_{x_i} reflects structural response function $F(X)$'s monotonicity to design variable x_i. The absolute value of S_{x_i} reflects structural response function $F(X)$'s sensitivity to design variable x_i; the greater this value is, the more sensitive to x_i the function $F(X)$ is. The precondition of equation (7) is that the modification of x_i must be very small. However, in practical application, difficulties in changing different design variables by same values vary, while difficulties in changing optimization variables by same percentages are basically the same. For example, when the material density is large and the pipe diameter is small, changing the material density by 0.1 is easier than changing the pipe diameter by 0.1. Therefore, this paper proposes the concept of pressure weight of idlers and takes this weight as the basis for optimizing parameters.

3.2. Weight Concept. For any multivariate differentiable function, the following equation can be derived using Taylor's expansion:

$$F(x_1, x_2, \ldots, x_n) = \left(\frac{\partial F}{\partial x_1}, \frac{\partial F}{\partial x_2}, \ldots, \frac{\partial F}{\partial x_n}\right)(x_1, x_2, \ldots, x_n)^T + H, \tag{8}$$

where H is a higher-order term.

The partial derivative term in equation (8) is function variable's sensitivity to function. When the higher-order term is ignored, the multivariate function can be approximated as

$$F(x_1, x_2, \ldots, x_n) \approx \frac{\partial F}{\partial x_1}x_1 + \frac{\partial F}{\partial x_2}x_2 + \cdots + \frac{\partial F}{\partial x_n}x_n. \tag{9}$$

After the weight vector $\boldsymbol{\lambda} = (\lambda_1, \lambda_2, \ldots, \lambda_n)^T$ is defined to make it become the percentage of function value corresponding to any one variable to total function value, the weight can be expressed as

$$\lambda_i = \frac{\partial F}{\partial x_i} \frac{x_i}{F(x_1, x_2, \ldots, x_n)}, \quad i = 1, 2, \ldots, n. \tag{10}$$

In optimization design, the pressure of idlers is usually the implicit function of various optimization design variables and can be expanded according to equation (10), where the partial derivative term is the sensitivity of pressure of idlers and the weight vector represents the "contribution" ratio of all variables to pressure of idlers. The larger the weight of the optimization variable is, the greater effect on idlers the variable has.

As can be seen in Figure 3, when the sensitivity is used as the basis of selection, the material density and belt width have a high sensitivity and the remaining parameters are small; when the weight is used as the basis of selection, the pipe diameter and material filling height have a great effect on the pressure of idlers. Obviously, the latter matches the actual situation better. Positive weights indicate that the pressure of idlers increases with the increase of the parameter, and negative weights indicate that the pressure of idlers increases with the decrease of the parameter.

The analysis results show that the variable that has a great effect on the pressure of idlers is pipe diameter and material filling height. Therefore, final optimization variables are determined to be pipe diameter and material filling height (filling rate).

4. Simulation and Experimental Verification

4.1. Discrete Element Simulation Analysis. The difficulty of separation of raw coal and mixed gangue after mining is increased due to the nonuniform particle size. Therefore, it is necessary to crush a large amount of raw coal and gangue before transportation by the pipe belt conveyor. In general, a jaw crusher can be used to crush large coal gangue to 18–48 mm [20]. Therefore, the simulation coal radius is 20 mm, and the conveyor belt model adopts the moving-plane model to simulate the uniform linear movement of the conveyor belt. In this paper, the recovery coefficient and static friction coefficient between coal and conveyor belt are set up with reference to document [22] the simulation process as shown in Figure 4.

Tables 1 and 2 are the pressure values of different measuring areas with filling rates of 60% and 75%.

4.2. Test Design. This test was set up on a self-designed hexagon pressure testing device with adjustable pipe diameter, which consists of 6 linear feed guides, 6 pressure sensors, 1 external eight-way signal transformer, and 1 eight-way paperless recorder, as shown in Figure 5. The relevant parameters are as follows: the adjustable range of pipe diameter is 150 mm~250 mm, the feeding of linear feed guides is 150 mm, and the support bracket is made of aluminum alloy with density of $2.66 \times 10^3\ \mathrm{kg/m^3}$ and thickness of 4 mm.

During the test, signals of 6 pressure sensors were detected within 150 mm~250 mm of pipe diameter at no load, 60% or 75% filling rate, and full load. Then, the pressure sensor's signals under different pipe diameters were obtained with the paperless recorder and computer, and the relevant data were processed with signal processing software [21]. The test principle and plan are shown in Figure 6.

4.3. Test Results and Discussion. Six pressure sensors' signals at no load, 60% or 75% filling rate, and full load were

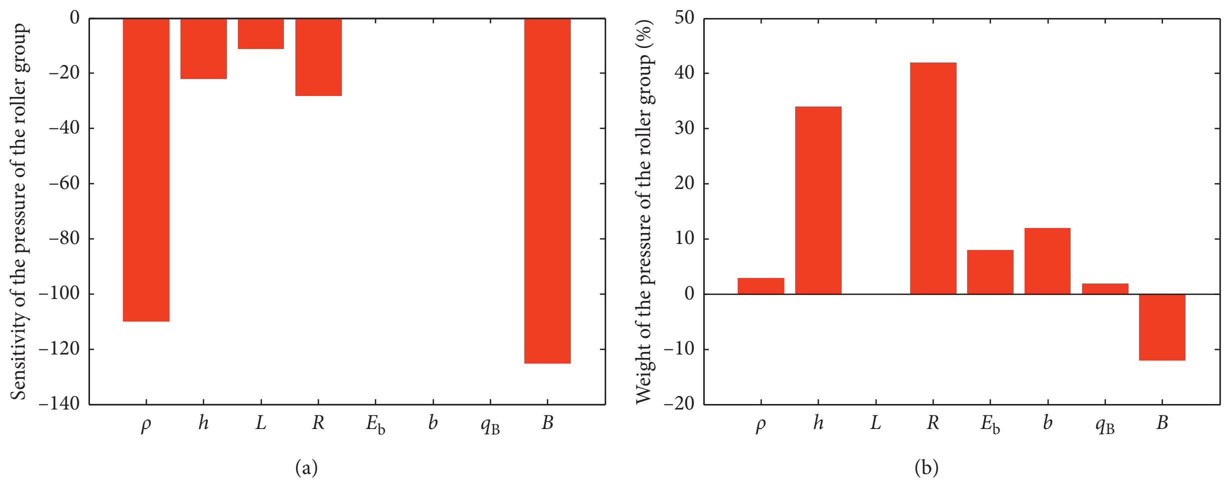

FIGURE 3: Simulation diagram. (a) Sensitivity of the structural parameters on the pressure of the roller group. (b) Weight of the structural parameters on the pressure of the roller group.

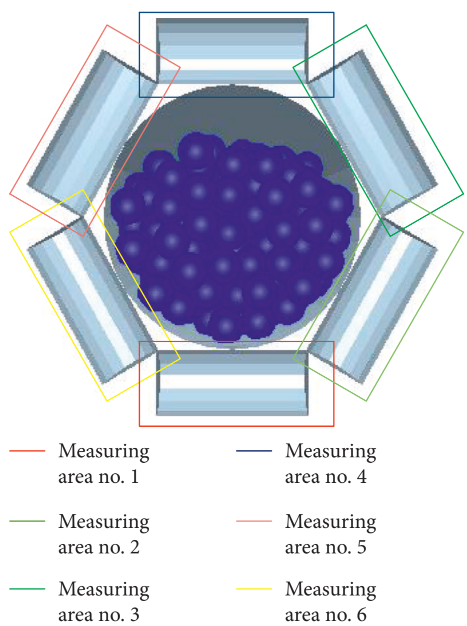

FIGURE 4: Simulation process.

TABLE 1: Pressure value of the roller group at 60% filling rate.

	150 mm	180 mm	210 mm	240 mm
Measuring area no. 1	49 N	58 N	73 N	107 N
Measuring area no. 2	30 N	40 N	69 N	79 N
Measuring area no. 3	17 N	19 N	18 N	20 N
Measuring area no. 4	9 N	12 N	13 N	15 N
Measuring area no. 5	7 N	11 N	19 N	30 N
Measuring area no. 6	38 N	65 N	74 N	131 N

researched and analyzed by processing the test data with MATLAB numerical analysis software, as shown in Figure 7.

Figures 7(a)–7(d) give the test results obtained at no load, 60% filling rate, 75% filling rate, and full load by

TABLE 2: Pressure value of the roller group at 75% filling rate.

	150 mm	180 mm	210 mm	240 mm
Measuring area no. 1	69 N	72 N	103 N	132 N
Measuring area no. 2	29 N	41 N	70 N	79 N
Measuring area no. 3	10 N	49 N	52 N	60 N
Measuring area no. 4	17 N	19 N	40 N	51 N
Measuring area no. 5	14 N	21 N	30 N	35 N
Measuring area no. 6	51 N	60 N	97 N	139 N

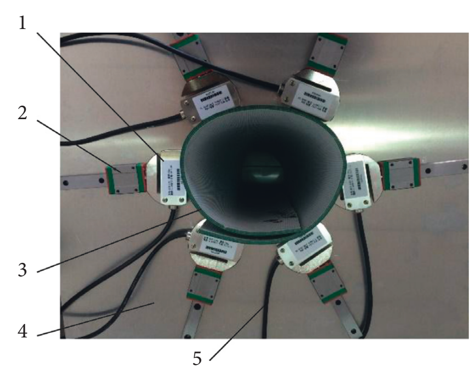

FIGURE 5: Test device. 1, pressure transducer; 2, linear feed guide; 3, conveyor belt; 4, bracket; 5, signal transmission line.

simulating the arrangement of hexagon idlers on 6 pressure sensors. As can be seen from Figures 7(a)–7(d), No. 1 and 6 are subject to the largest pressure and unequal forces; No. 2 and 5 are subject to a large pressure and unequal forces; No. 3 and 4 are subject to the smallest pressure and unequal forces; the whole force increases with the increase of pipe diameter although each idler has different force trends. It can be known from the comparison of Figures 7(a)–7(d) that when the filling rate and pipe diameter gradually increase, idlers' force simulated by pressure sensors increases as a whole, but the force distribution of each idler in idlers varies, which are consistent with the actual situation.

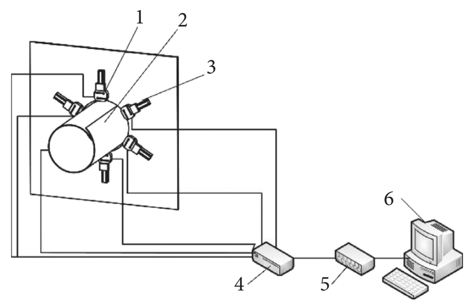

FIGURE 6: Schematic diagram of experimental test. 1, pressure transducer; 2, conveyor belt; 3, linear feed guide; 4, signal processor; 5, paperless recorder; 6, PC.

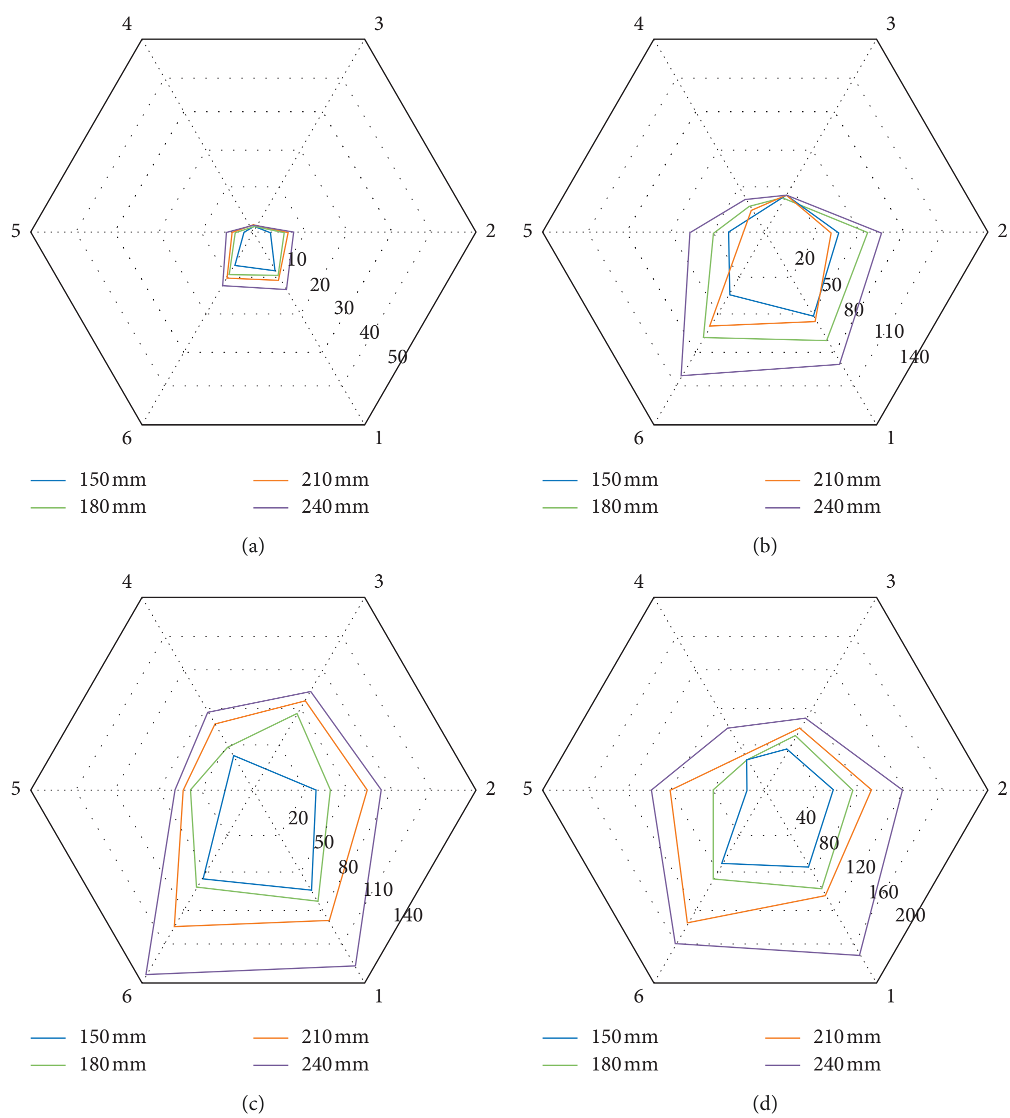

FIGURE 7: Pressure diagram of the roller group under different pipe diameters: (a) no load, (b) 60% filling rate, (c) 75% filling rate, and (d) full load.

The pipe diameter is set at 150 mm. Table 3 is the comparison data table between the simulation value and the test value when the filling rate is 60% and 75%, respectively.

From Table 3, we can see that the simulation value of the idler group is close to the test value, and the average error is only 7.3%. From Figure 8, it can be concluded that the

Table 3: Comparison of simulation and test results.

		Pressure simulation (N)	Pressure test (N)	Error (%)
1	60%	49	54	9.1
	75%	69	70	1.5
2	60%	30	32	6.7
	75%	29	32	9.4
3	60%	7	7	0
	75%	10	11	9.1
4	60%	9	10	10
	75%	17	19	10.5
5	60%	8	9	11.1
	75%	14	15	6.7
6	60%	38	40	5
	75%	51	56	8.9
Average error		—	—	7.3

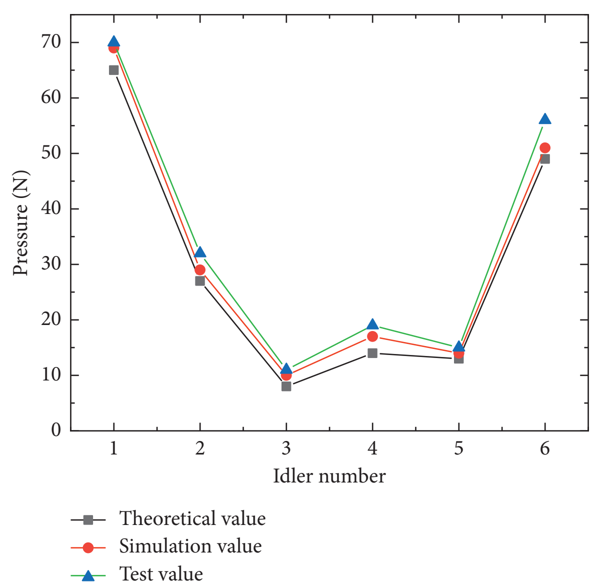

Figure 8: Pressure comparison of theoretical, simulation, and test rollers.

theoretical and simulated values of the pressure of the idler group are in good agreement with the experimental values, and the values are close to each other. The main sources of errors in test results, theory, and simulation analysis are neglecting the length of the overlapping area after the conveyor belt of the pipe belt conveyor becomes circular and the bending rigidity of the conveyor belt.

5. Conclusions

In this paper, a pressure testing device for the hexagonal adjustable idlers was proposed to solve the difficulty in measuring the nonuniformly distributed pressure generated by the pipe belt conveyor when conveying raw coals. Moreover, a mechanical model of the bottom-type idlers of the pipe belt conveyor was established. Then, the sensitivity analysis on the factors influencing the pressure of the idlers was completed to reduce the workload of the mechanical analysis of the idlers. The main control factors were then found based on the weighting to be the pipe diameter and the filling rate. Finally, the conclusions of the theoretical analysis were verified through a series of simulations and tests. The specific conclusions are as follows.

(1) The mechanical model of the pinch-bottom idler group of the circular pipe belt conveyor is established by using the microelement method. In order to reduce the workload of mechanical analysis of the idler group, the sensitivity analysis of mechanical model of the idler group is carried out, and the pipe diameter and filling rate are obtained as the main controlling factors of the pressure of the idler group.

(2) Self-designed test is used to simulate the stress of the hexagonal roller group, and the force distribution of the hexagonal roller group and the dynamic force diagram of the hexagonal roller group under different filling rates are obtained. Comparing the force simulation value with the test value of the hexagonal roller set shows that the average error between them is only 7.3%. The research provides theoretical reference and experimental basis for the design of raw coal conveying of the circular pipe belt conveyor.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interests regarding the publication of this paper.

Authors' Contributions

Shuang WANG conceptualized the study; Shuang WANG and Deyong LI formally analyzed the results; Shuang WANG and Kun HU obtained the funding; Deyong LI wrote the original draft.

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