A Study of the Operation Parameters of a Tube Chain Conveyor Based on Discrete Element Simulation

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Abstract. Computer simulation design can be utilized to determine operation parameters for tube chain conveyors (TCCs), such as a reasonable material filling rate and running speed of the scraper chain; this approach can shorten the developing cycle of TCCs and reduce developing costs. This study chose three material filling rates (75%, 60%, and 50%) and the corresponding running speeds of the chain (0.37 m/s, 0.47 m/s and 0.57 m/s) as research variables. Using simulation software implementing the engineering discrete element method (EDEM), we obtained the chain tension values during material conveyance. By comparing these values with those obtained in a field experiment measurement under the aforementioned conditions, we conclude that the EDEM simulation results are consistent with the experimental measurement results. This study demonstrates that it is plausible to simulate different operation parameters of TCCs using EDEM simulation, which provides a computer design method for rationally determining the operation parameters of TCCs.

1. Introduction

The tube chain conveyor (TCC) conveys the material using a scraper that is fixed on the chain [1]. The TCC has good route adaptability and is considered an innovative transmission route technology revolution. Currently, the TCC has a small range of applications, due to the relatively slow progress of TCC research and the lack of a corresponding design theory and effective computer simulation design methods [2].

To achieve a certain production capability, the operating parameters of TCCs, such as the material filling rate and running velocity of the scraper chain, are not unique but correspond to parameter combinations. Different operation parameters affect the operating performance of TCCs and the stability of materials in the conveyance.

At present, studies on TCCs include those of Krause, Banse, Schmolke and Werner. A from Institut für Förder- und Baumaschinentecnik, Stahlbau und Logistik (IFSL). These researchers used wheat and flour as conveying objects, created TCC samples, and performed a chain tension test on TCCs. A self-made wireless strain gauge was fixed on the scraper side, and the tested system was made to revolve with the hauling component in a closed trough. Operation data were collected to obtain signals in the closed trough. This experiment provides a method for testing the chain tension in a closed trough [3, 4]. By studying the physical properties of bulk materials and their effect on the performance of the TCC and using DEM simulation and the variation curve of the chain tension, these researchers concluded that the magnitude of the chain tension is related to the material attributes and filling rate [5-7]. This study lays a solid foundation for the application of discrete element software to TCCs. However, further systematic research is required to determine the operation parameters of a TCC.
Using computer simulation, the optimal operation parameters of a TCC can be quickly determined, thus shortening the design cycle of the TCC and improving its operating performance.

This study used discrete element simulation software to simulate three sets of TCC parameters whose material filling rates were 75%, 60%, and 50%, with chain operation speeds of 0.37 m/s, 0.47 m/s, and 0.57 m/s, respectively, to improve the use of computer simulation design methods. We obtained different operation parameters corresponding to the force-loading curve of the wire rope and operation parameters of the TCC corresponding to stable operation of the wire rope with minimum stress. The chain tension and machine power consumption were then experimentally obtained using the aforementioned operation parameters. Finally, the experimental results and simulation results were compared, which verified the accuracy of the engineering discrete element method (EDEM) and its suitability as a rapid and rational computer design method for TCCs.

2. Experimental Methods

2.1. Theoretical Background
The EDEM is a discontinuous medium mechanical numerical method that separates a discontinuity into a set of rigid elements; this approach enables each rigid element to satisfy the motion equation, uses the step length iteration method to solve the motion equation for each rigid element, and obtains the overall motion modality of the discontinuity [8, 9]. The EDEM provides an explicit solution, which applies classic Newtonian laws to analyze the interaction among discrete particle elements and uses the static and dynamic relaxation iteration method to calculate the displacement of all discrete particle elements for a given time step and force situation. Then, the positions of all particle elements are recalibrated. By tracing the microscopic motion of each discrete particle element, the macroscopic motion state of the entire ‘continuous medium’ is calculated [10-14].

2.2. Simulation Process
The interaction between links was neglected, and wire ropes were used instead of chains to establish a three-dimensional model of the TCC, as shown in figure 1. The scraper diameter was 200 mm, the scraper pitch was $2 \times 92$ mm, the tube trough was $219 \text{ mm} \times 6 \text{ mm}$, and the productivity was 40 t/h [2, 15]. The simulation parameters are shown in table 1.

Soybean was used as the object in the simulation study. The tetrahedral configuration method was used to create an ellipsoidal particle model, which can more genuinely and effectively simulate the operation of the TCC when conveying soybeans (figure 2) [16]. The materials were selected according to the parameters in tables 2 and 3, and other attributes were automatically obtained.

![Figure 1. Three-dimensional model of the TCC.](image-url)
Table 1. Basic parameters for the TCC and its simulation

| Basic TCC parameters | Running speed of the scraper chain \( v \) (m/s) | Material filling rate \( \eta \) (%) |
|----------------------|-----------------------------------------------|----------------------------------|
| \( Q =40 \text{ t/h} \)                  | 0.38                                           | 75                               |
| \( L =25 \text{ m} \)                      | 0.47                                           | 60                               |
| \( \gamma =12280 \text{ N/m} \)              | 0.57                                           | 50                               |
| Scraper diameter \( D =200 \text{ mm} \)       |                                               |                                  |
| Scraper pitch \( t =184 \text{ mm} \)           |                                               |                                  |

Table 2. Attributes of soybean and trough materials.

| Material  | Density (kg/m\(^3\)) | Poisson’s ratio | Shear modulus (MPa) |
|-----------|------------------------|-----------------|---------------------|
| Soybean   | 1228                   | 0.25            | 1.04                |
| Steel     | 7800                   | 0.30            | 7×104               |

Table 3. Material contact attributes.

| Contact           | Static friction coefficient | Rolling friction coefficient | Recovery coefficient |
|-------------------|-----------------------------|------------------------------|----------------------|
| Soybean-soybean   | 0.45                        | 0.05                         | 0.6                  |
| Soybean-steel     | 0.3                         | 0.01                         | 0.6                  |

A virtual rectangular particle factory was created on top of the funnel to define the area of particle production in the model. A dynamic method was utilized to generate the particle factory. The transmission rate of soybean particle production was set at 10,000 pieces/second, which generated 32,000 pieces in total. The particle diameter size followed the normal distribution mode, and the maximum number of attempts to place particles was 20 [9].

The simulation time step was set at 13% (4.20689×10\(^{-5}\) s), and the fixed time step was set at 13%. The total simulation time, which represented the actual time, was set at 4 s, and the write-out time interval was set at 0.01 s. The grid size was set at 4 Rmin in the study.

2.3. Experimental Verification

The equipment in the study included a TCC, a DH-5922 Dynamic Signal Analyzer manufactured, computers, etc. The experimental site is shown in figure 3.

This study primarily focused on the stress of corresponding chains for material filling rates of 75%, 60%, and 50% while satisfying the requirement of a certain production capacity.
The conveyance capacity of the TCC was $Q=40$ t/h, the conveying distance was 25 m, the tube trough dimensions were $219 \text{ mm} \times 6 \text{ mm}$, the pitch of the scraper chain was 92 mm, the allowable load of the chain was $1/6$ of the breaking load of the chain, the pitch of the scraper chain was $2 \times 92 \text{ mm}$, the motor power was 15 kW, and the transmission ratio of the reducer was 160.

As indicated in figure 4, the strain gauge was attached to Link 1 and moved forward with the scraper chain. Tension Testing Line 2 was fixed along the bearing branch scraper and chain. This line was led out at the top opening and connected to a dynamic signal analyzer, strain gauge and PC through the strain compensation gauge. The strain curve of the links was output by the PC.

3. Results

3.1. EDEM Simulation Results
The force curves of the wire core at different filling rates are shown in figure 5. The average values of stress sustained by the wire core are shown in table 4.

Based on figure 5, the results for $\eta=75\%$ and $\eta=60\%$ were obtained. The force change on the wire core was notably even, and the operation of the wire core was fairly stable. When $\eta=50\%$, the force on the wire core exhibited sudden changes, which caused the wire core to jitter or vibrate, and consequently, the materials also vibrated. This operation instability increased the power consumption.

| Material filling rate $\eta$ | 75%   | 60%   | 50%   |
|-----------------------------|-------|-------|-------|
| Average stress (105 N)      | 0.015812 | 0.019162 | 0.025016 |

3.2. Experimental Results
Chain strain curves of the TCC at different filling rates and chain operating speeds were obtained experimentally at the same location.

From table 5, the following findings are obtained:
Table 5. Strain peaks at different channels under identical testing conditions.

| Filling rate | Average value of Strain 1 $\varepsilon_1$ (με) | Averages value of Strain 2 $\varepsilon_2$ (με) | $\varepsilon_1-\varepsilon_2$ (με) |
|--------------|---------------------------------------------|---------------------------------------------|---------------------------------|
| 75%          | 2104.91                                    | 2109.8                                     | 4.89                            |
| 60%          | 2396.86                                    | 2332.4                                     | 35.54                           |
| 50%          | 2637.72                                    | 2799.28                                    | 161.56                          |

An enormous amount of data was obtained in the experimental measurement. In the measurement, some objective factors were observed, such as vibration caused by chain meshing and material particles clogged in the gap between the scraper and the trough. These factors increased the frictional force, which increased the tension in the measurement [17].

The simulated values obtained from the EDEM are smaller than the experimental results. Both the simulation process and the simulation model assume an ideal state. After the parameters are set, the values are constant. However, in the experiment and in actual operation, the frictional coefficients vary due to factors such as processing, installation and usage.

In table 6, when $\eta=75\%$, the chain tension and motor power are at their minimum. When $\eta=50\%$, these values reach a maximum.

Table 6. Statistics of testing and data calculation.

| Conveying capacity $Q=40$ t/h $L=25$ m | $\eta=75\%$ $v=0.38$ m/s | $\eta=60\%$ $v=0.45$ m/s | $\eta=50\%$ $v=0.57$ m/s |
|----------------------------------------|---------------------------|---------------------------|---------------------------|
| Mean tension of chain (kN)             | 2.27                       | 2.4                       | 2.9                       |
| Power required (kW)                    | 5.56                       | 6.64                      | 7.84                      |
| Measurement results                    | 2.04                       | 2.68                      | 3.11                      |
| Power required (kW)                    | 5.49                       | 6.48                      | 7.75                      |

In conclusion, when $\eta=75\%$, the conveyance plan is optimal in both the EDEM simulation and the experiment. When $\eta=60\%$, the performance is relatively good. When $\eta=50\%$, the performance is the poorest.

4. Discussion
To promote the application of TCCs and to resolve the shortage of computer design methods for TCCs, this study used EDEM software to perform simulations when the material filling rate and running speed of the scraper chain of a TCC were $\eta=75\%$, $v=0.37$ m/s; $\eta=60\%$, $v=0.47$ m/s; and $\eta=50\%$, $v=0.57$ m/s. This study also obtained experimental measurements. Based on the wire core tension and power consumption, the optimal combination of operation parameters was determined, and a computer design method was provided for TCCs.

As the German scholars have noted, when a TCC is conveying materials, the chain tension is related to the material filling rate but not the running speed of the scraper chain. However, these researchers have not provided a specific relationship between the chain tension and the material filling rate [5-7]. This study draws the following conclusions based on EDEM computer simulation and experimental measurement and establishes a relationship between the material filling rate and the chain tension: when $\eta$ is less than 75%, the chain tension increases as the material filling rate decreases.

(1) When $\eta=75\%$, the tension curve of the chain is flat, with the minimum average tension and stable operation. When $\eta=60\%$, the curve of the chain tension changes more apparently than when $\eta=75\%$, with a larger average tension and relatively stable operation. When $\eta=50\%$, the curve of the
chain tension shows the greatest change with the largest average tension and extremely unstable operation. Therefore, the smaller filling rate is not better when the TCC conveys materials. Ref. [2] also reported similar results. When the material filling rate is too small, the chain vibration is severe. Unstable operation aggravates the friction between the scraper and the trough, causes larger additional running resistance, and renders the materials prone to damage during conveyance. Therefore, the material filling rate is generally set at 70-80%.

(2) The chain tension and machine power values in the experiment are larger than the EDEM simulation results due to objective factors in the measurement, such as vibration caused by chain meshing and material particle clogging between the scraper and the trough, which increase the frictional force and measured tension. The EDEM simulation results tend to be smaller than the experimental data because both the simulation and the simulated model assume an ideal state. After the parameters are set, their values are constant. However, the actual frictional coefficients may change because of factors such as manufacturing, installation and usage.

Due to a limited time schedule, this study did not analyze EDEM simulations for a wider range of material filling rates. In the future, we will perform simulated studies for different materials and filling rates to derive a normal distribution relationship between the chain tension and the material filling rate and to provide full guidance for the design of TCCs.

5. Conclusions
This study has established a visualized three-dimensional model for TCCs using Solidworks. We conducted a simulation study based on EDEM software and obtained the average tension curve of the wire core of a TCC during operation. We found that when $\eta = 75\%$, the tension variation of the wire core was even, and the wire core exhibited steady operation. When $\eta = 50\%$, the tension of the wire core showed sudden variations, indicating unsteady operation. In the on-site experimental measurement of the link strain, we found that when $\eta = 75\%$, the chain tension and motor power are at a minimum. When $\eta = 50\%$, these values reach a maximum. The EDEM simulation results are consistent with the experimental results and fully demonstrate the plausibility of applying infinite discrete element software to the simulation study of TCCs. This study has provided a simplified and efficient computer simulation design method for optimizing the operation parameters of a TCC. This method can be used to simulate chain tension values for large-scale TCCs when delivering materials. Based on the operational stability, the designed operation parameters can be determined, improving on the current situation in which operation parameters are determined based on experience and enhancing the design method and machine operation performance of TCCs.

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