OPTIMIZATION OF THE STRUCTURE OF THE MILK POWDER CONVEYING DEVICE FOR CALF FEEDING EQUIPMENT BASED ON DISCRETE ELEMENT SIMULATION
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基于离散元仿真的犊牛饲喂装备代乳粉料输送装置结构的优化

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ABSTRACT
In the intelligent transformation of global animal husbandry, precise calf feeding faces challenges like arching and flow fluctuations during milk replacer delivery, leading to inaccurate feeding, diarrhea and higher costs. This study aims to enhance the precision and stability of milk replacer delivery via structural innovation. Through shear tests, the internal friction angle of milk replacer was measured at 23.76° and the external friction angle at 23.97°. Combined with discrete element simulation and orthogonal experiments, the scraper conveyor device was optimized. A particle model of milk replacer was established using the discrete element method to analyze the effects of blade curvature, number of blades and guide plate tangent angle on conveying performance. Optimal parameters were determined through orthogonal experiments. Results showed that the guide plate tangent angle most significantly affected conveying rate, with peak efficiency at 45°. The number of blades was the main factor for operational stability, with 8 blades reducing delivery fluctuations. The optimal combination was found to be curved blades, 8 blades and a 45° guide plate tangent angle. Validation tests showed a stable conveying rate of 7.50 - 8.48 g/s, a standard deviation below 0.43 g, and operational stability of 71.80% - 75.96%, effectively solving arching and flow fluctuation issues. This study offers theoretical support for developing precise powder delivery equipment and core technological support for domestic smart feeding equipment. It directly helps reduce calf morbidity and improve ranch economic efficiency.

摘要
面对全球智能化转型中犊牛精准饲喂的技术瓶颈，针对代乳粉输送过程因结拱、流量波动导致的饲喂精度不足、犊牛腹泻率上升及养殖成本增加等突出问题，本研究旨在通过结构创新提升犊牛饲喂过程中代乳粉料输送精确性和稳定性。通过直剪试验测定代乳粉内摩擦角为23.76°、外摩擦角为23.97°的实测数据，结合离散元仿真与正交试验，系统优化刮板式输送装置。采用离散元法建立代乳粉颗粒模型，系统分析叶片曲率变化、叶片数量及导流板切向角对输送性能的影响规律，并通过正交试验确定最优参数组合。结果表明：导流板切向角对输送速率影响最为显著，切向角为 45°时效率最高；叶片数量是运行稳定性的主控因素，8 片叶片工况下有利于降低粉料输送的波动率。最终确定圆弧叶片、8 叶片、45°导流板切向角为最优组合，试验验证显示输送平均速率稳定于 7.50-8.48g/s，标准偏差小于 0.43g，运行稳定性达 71.80%-75.96%，有效解决了结拱与流量波动问题。本研究为高黏性粉料精准输送装备开发提供了理论依据。为智能饲喂装备国产化提供核心技术支持，对降低犊牛发病率、提升牧场经济效益具有直接应用价值。

INTRODUCTION
As the global livestock industry accelerates its transformation towards intensification and digitalization, precision feeding technology for dairy cows has emerged as a key component in enhancing both farm production efficiency and animal welfare standards *(Meng et al., 2013)*. The vital role of scientific precision feeding for calves in promoting rumen development and reducing feeding costs has become a critical component of modern ranch management *(Zeng et al., 2017)*. Traditional bucket-based management models relying on manual operations present challenges such as significant temperature fluctuations during feeding, inconsistent feed quantities, and hygiene management difficulties, which may lead to health risks including calf diarrhea and impaired growth. Livestock and poultry breeding feeding robot technology faces both challenges and opportunities in improving feeding efficiency and enhancing animal health levels *(Dmytriv Vasyl et al., 2020, Dmytriv Ihor et al., 2021, Bin et al., 2021)*.

Companies such as Germany-based FörsterTechnik and Sweden's DeLaval have developed intelligent feeding systems for calves, utilizing RFID and distributed control systems to achieve individualized feeding protocols (*Zhao et al., 2015, Janzekovic M. et al., 2011, Sutherland M. et al., 2018). Yang et al., (2016), Cai et al., (2014), Zhang et al., (2016),* have conducted comprehensive research and analysis on automated feeding systems for sheep, meat pigeons, hogs, and other livestock species, significantly contributing to the technological advancement of intelligent feeding devices. The intelligent calf feeding apparatus designed by *Qi et al., (2014),* enables customized control parameter settings based on individual calf biometrics, achieving precise water volume metering, temperature-regulated formula preparation, and automated incorporation of measured milk replacer doses, with liquid feed homogenization accomplished through an integrated agitation mechanism. *Jin et al., (2014),* designed a liquid feeding control system for calves, utilizing a MCU as the central control system. It employs DS1820 sensors to monitor and regulate temperature through feedback mechanisms, achieving precise control of milk temperature. *Shi et al., (2016),* have successfully developed a precision calf feeding control system based on a host-slave architecture, achieving fully automated temperature-stabilized and quantity-regulated feeding of regular milk. *He et al., (2022),* developed a dynamic temperature control system based on a fuzzy PID control algorithm to achieve precise regulation of reconstituted milk replacer solution temperature during calf feeding processes, significantly improving the control accuracy of heat exchanger temperature. The team has currently designed a B/S architecture-based calf feeding information management system for operational data management, while constructing predictive models for milk allowance and replacer concentration parameters. These advancements collectively enhance intelligent and precision management levels in calf rearing operations at dairy farms *(He et al., 2022)*.

As the core nutritional carrier for calves, milk replacer requires precise conveyance and metered feeding that directly influence calf growth performance and health status. However, technical bottlenecks persist in achieving uniformity and controllability of replacer delivery systems, leading to recurrent bridging phenomena and discharge fluctuations. These operational instabilities compromise feeding accuracy and indirectly hinder precision management protocols in calf rearing operations. Current research on conveying equipment predominantly focuses on conventional configurations such as screw-type and vibratory-type systems. While screw conveyors feature simple structural configurations, they exhibit proneness to bridging tendencies when handling poor-flowability powder materials. Additionally, insufficient precision in motor speed regulation results in discharge quantity deviations *(Meng et al., 2015, Wang et al., 2011)*. While vibratory conveyors can mitigate bridging issues in powder conveyance, they are prone to excessive material spillage that causes environmental contamination and feed wastage *(Su et al., 2013)*. In comparison, scraper-type conveyors demonstrate potential through their uniform material propulsion and low residual accumulation characteristics. However, prevalent designs suffer from material adhesion issues and premature scraper blade wear. Research by *Li et al., (2014),* has demonstrated that the nonlinear relationship between scraper rotational speed and conveying rate is prone to induce flow fluctuations. *Qiao et al., (2014),* have identified that the optimization of scraper spacing constitutes a critical factor in enhancing operational efficiency.

Current research lacks systematic investigation into the coupling mechanisms between key parameters of scraper-type conveyors and powder motion characteristics, particularly for materials like milk replacer with distinctive frictional properties. The optimization of conveying efficiency and stability for such materials remains inadequately supported by theoretical foundations. This study addresses these gaps by employing the Discrete Element Method (DEM) to investigate discharge uniformity in milk replacer feeding systems. A systematic analysis has been conducted on the effects of flow-guiding baffles and conveyor structural configurations on conveying rates and operational stability within storage units. Optimal operational parameters for calf feeding machine conveying systems have been determined through parametric analysis. The resolution of dynamic bridging phenomena during milk replacer conveyance establishes a generalizable methodological framework for precision conveying system design of complex powdered materials. These findings provide practical significance for enhancing intelligent livestock equipment and advancing industrial transformation.

MATERIALS AND METHODS

Milk replacer material characteristics

The experimental material was calf-specific milk replacer with a moisture content of 5.84 wt.% (Brand: Nongdali; Composition: concentrated whey protein, whey powder, fat, vitamins, minerals, amino acids, enzymatic preparations).

The design of milk replacer conveying systems necessitates comprehensive understanding of the tribological properties of the stored material. Stress analysis was performed on the hopper assembly and agitator blades based on these frictional characteristics, as experimentally validated in Fig. 1, thereby enabling rational structural design of the powder conveying system.

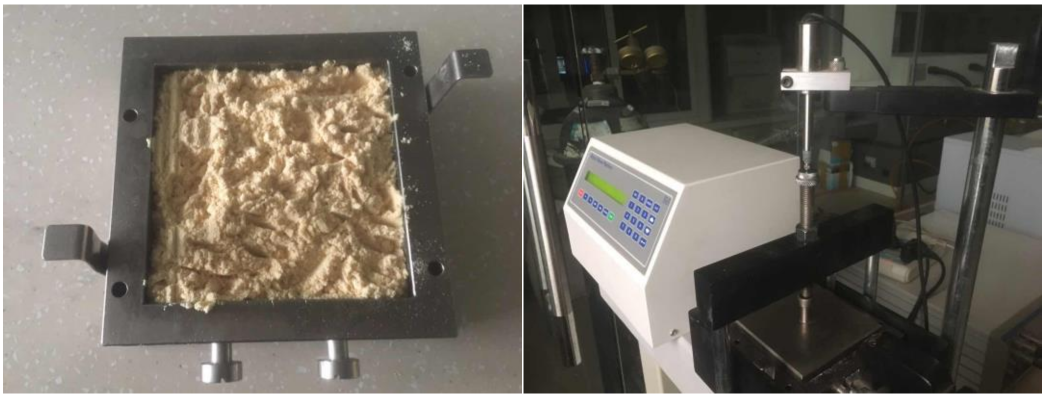


Fig. 1 – Milk replacer and direct shear test apparatus diagram

Experimental measurements of the internal friction characteristics of milk replacer powder and its external friction characteristics against stainless steel plates were conducted. Through linear regression analysis, the internal friction angle of the material was determined as 23.76°, with the wall friction angle measuring 23.97°.

Model development and parameter configuration of scraper-type conveyor systems

The design of the conveying system primarily considers three aspects: effective conveying volume, the resultant radial forces exerted by blades and flow-guiding baffles on materials, and the influence of the number of blades on conveying speed fluctuations. The scraper-type conveyor is shown in Fig.2.

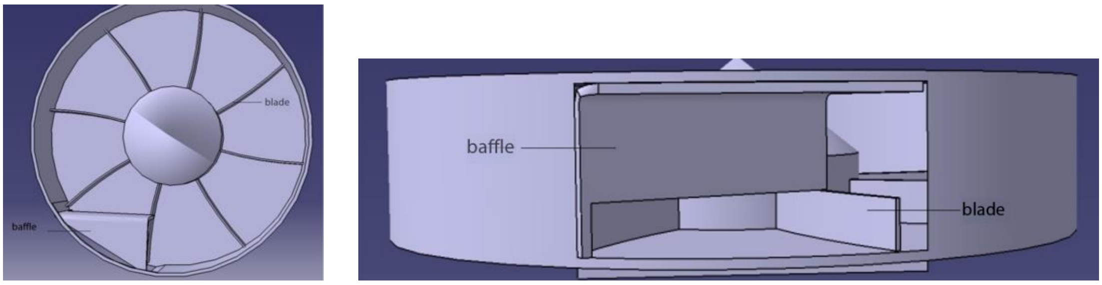


Fig. 2 – Milk replacer and direct shear test apparatus diagram

For effective conveying volume, since the height of the discharge port is fixed, it is mainly determined by the projected area variation along the axial direction of the hopper formed by the blades and baffles. The baffle angle and blade shape both affect this effective area.

Regarding the resultant radial forces from blades and baffles, when the angle between the baffle and the radial direction of the hopper decreases, the radial component force exerted by the baffle on the material also decreases. Although this increases the effective conveying volume, insufficient radial force leads to reduced conveying efficiency. Excessively large baffle angles diminish the effective working volume by affecting material guidance. Similarly, blade effects on conveying must also consider their radial force components.

Analysis of the impact of blade number on conveying speed fluctuations. During material conveyance by the hopper's conveying system, the discharge rate exhibits non-uniform fluctuations influenced by blade geometry, flow-guiding baffle angles, and the number of blades. As the blades are uniformly distributed circumferentially, these fluctuations demonstrate periodic characteristics. Increasing the number of blades reduces the fluctuation period. Under ideal conditions with identical blade configurations and baffle angles, fluctuation profiles remain consistent over equivalent operational durations. Extended blade engagement periods result in prolonged fluctuation cycles, where amplitude variations exceed or equal those observed in systems with higher number of blades (shorter cycles).

Given the potential influence of blade curvature radius on discharge rate and uniformity, the factor levels were designed based on the curvature radius parameters of the blades. The polar coordinate equation of the logarithmic spiral is

$$\rho(\theta) = ae^{\theta cot\alpha} \tag{1}$$

where : ρ is the radial distance;

θ — the polar angle;

α — the helix angle;

a — the scale factor.

The logarithmic spiral is a curve where the radius of curvature is proportional to the polar radius. When α is 90°, the curve degenerates into a circular arc. The inlet setting angle for blades relative to the inner circumference is uniformly configured at 90°.

The mathematical formulation of logarithmic spirals and their engineering implementation in blade profile design are detailed as follows:

$$\begin{cases} x = 40cos(t)exp(tan\alpha \cdot t) \\ y = 40sin(t)exp(tan\alpha \cdot t) \end{cases} \tag{2}$$

where α is the helix angle;

x —the abscissa of blade curve;

y — the ordinate of blade curve;

t — the intermediate variable.

Particle characteristic parameter configuration and particle factory establishment

The milk replacer model complies with GB/T 20715-2006 standards for calf milk replacer. The parameters for Replacing particles and Stainless steel are shown in Table 1. The established particle is shown in Fig. 3. A region was established above the scraper-type conveyor model to accommodate the particle factory, as indicated by the green area in Fig 4. The particle factory generated 10,000 particles within 2 seconds.

Table 1

The parameters for Replacing particles and Stainless steel

Parameter	Values
Poisson's ratio of milk replacer particles	0.45
Bulk density of milk replacer particles /(kg·m^{-3})	500
Density of stainless steel /(kg·m^{-3})	7930
Shear modulus of stainless steel / (GPa)	77
Coefficient of restitution between milk replacer particles	0.01
Coefficient of restitution between milk replacer particles and stainless-steel	0.01
Sliding friction coefficient between milk replacer particles	0.44
Sliding friction coefficient between milk replacer particles and stainless-steel	0.4446

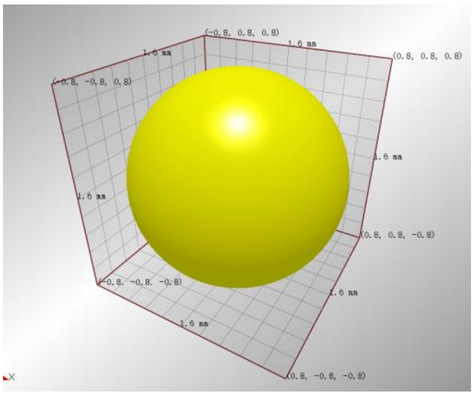


Fig. 3 – The established particle

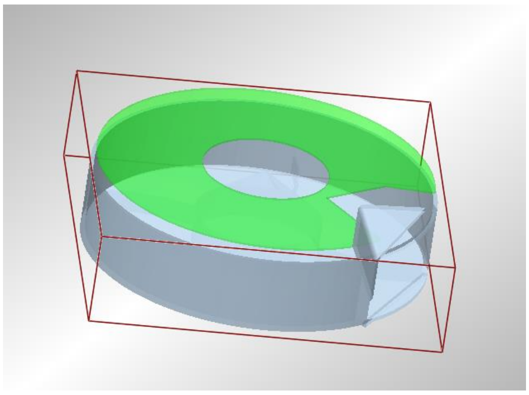


Fig. 4 – The particle factory

Discrete Element simulation of powder conveying

Based on the preceding analysis, a factor-level table has been established with variations in blade curvature radius, number of blades, and tangential angle between flow-guiding baffles and the conveyor as experimental factors, as detailed in Table 2. Simulation trials were conducted, with the computational process illustrated in Fig. 5.

Table 2

Factor-level table

Factors	A The blade curvature radius (α) (°)	B Number of blades (unit)	C Tangential angle between flow-guiding baffles and conveyor (°)
-1	30，gradually decrease	4	15
0	0	6	30
1	30，gradually increase	8	45

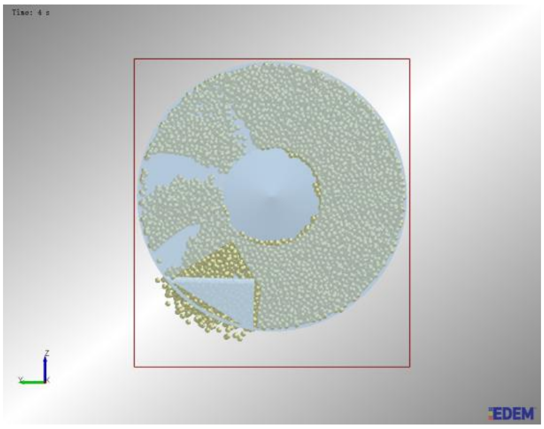
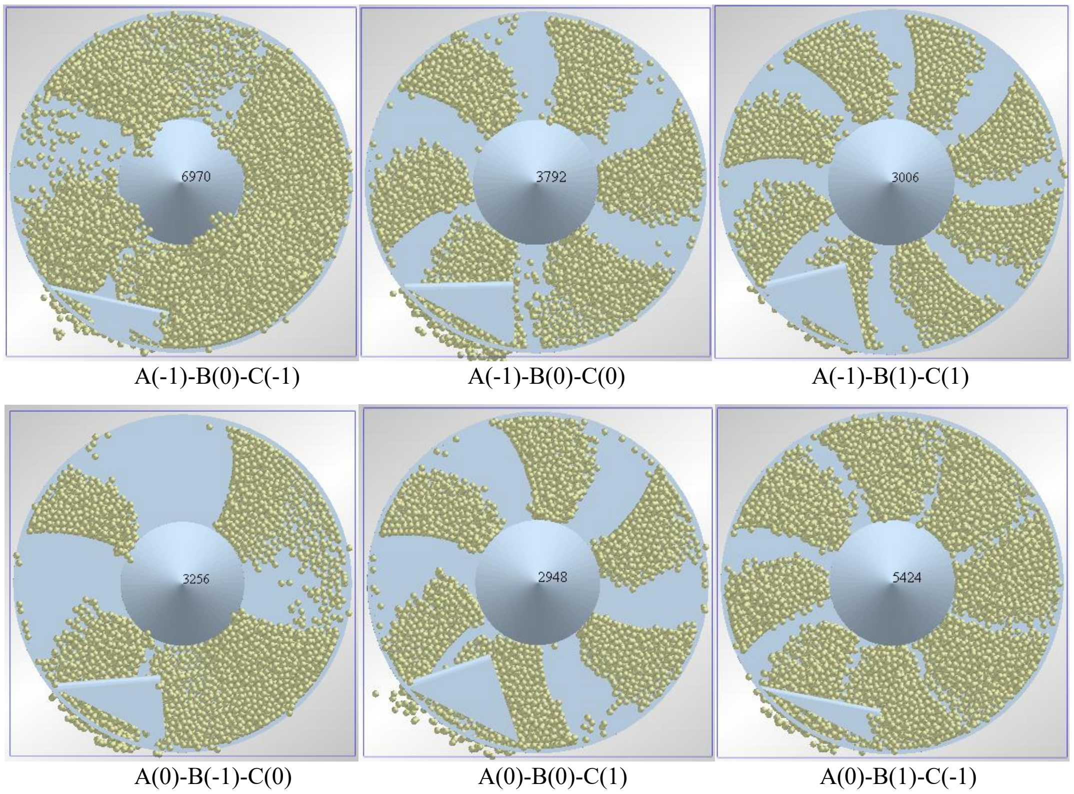


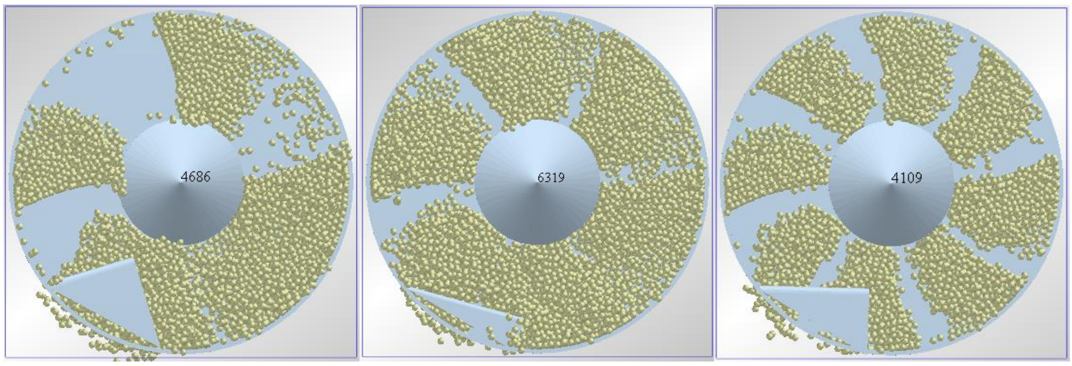
Fig. 5 – Powder conveying simulation process

RESULTS

Discrete Element simulation results of powder conveying

The intermediate phase was defined from 3.5 s to 9.5 s, during which the scraper blades completed exactly one full 360° phase rotation, i.e., all blades executed one operational cycle. Fig. 6 illustrates the residual material within the conveyor at 9.5 s.





A(1)-B(-1)-C(1) A(1)-B(0)-C(-1) A(1)-B(1)-C(0)

Fig. 6 – Residual material within the conveyor at 9.5 s

Simulation results indicate that when the tangential angle between flow-guiding baffles and the conveyor is 15°, residual material volume within the conveyor remains significantly higher. This demonstrates that the 15° configuration results in an excessively small effective conveying volume, impeding material transport. Conversely, negligible differences in performance are observed at 30° and 45° angles.

To determine the primary and secondary influences of each factor on powder conveying rate and operational stability, identify optimal levels, and ascertain the optimal parameter combination, a range analysis was performed on the simulation trials. The results are presented in Table 3.

Table 3

Orthogonal simulation results and range analysis

Indicator	Trial sequence number	A	B	C	Mid-term rate/(g/s)	Mid-term stability/(%)
	1	-1	-1	-1	21.36	36.96
	2	-1	0	0	46.6	73.77
	3	-1	1	1	47.09	65.26
	4	0	-1	0	28.34	37.24
	5	0	0	1	52.27	75.14
	6	0	1	-1	33.84	71.69
	7	1	-1	1	40.85	52.29
	8	1	0	-1	27.45	31.16
	9	1	1	0	43.51	69.01
Mid-term rate	K1	38.35	30.18	27.55		
	K2	38.15	42.11	39.48		
	K3	37.27	41.48	46.74		
	R	1.08	11.92	19.19		
Mid-term stability	K1	58.66	42.16	46.60		
	K2	61.36	60.02	60.01		
	K3	50.82	68.65	64.23		
	R	10.54	26.49	17.63		

Based on the mid-term experimental results, the optimal parameter combination includes a blade curvature radius of 30° with a gradual decrease, six blades, and a tangential angle of 45° between the flow-guiding baffles and the conveyor. Among the factors analyzed, the tangential angle had the greatest influence on conveying performance, followed by the number of blades, while blade curvature radius showed the least significant effect.

Based on mid-term stability results, the optimal parameter combination features a blade curvature radius of 0°, 8 blades, and a 45° tangential angle between flow-guiding baffles and conveyor, with the number of blades exhibiting the most pronounced effect on stability, followed by the baffle tangential angle, while blade curvature radius demonstrates the lowest significance.

The results of the orthogonal experiment ANOVA are presented in Table 4. Using mid-term conveying rate as the evaluation index and treating the empty column as the error term at a 0.05 significance level, the analysis shows that the flow-guiding baffle angle has a statistically significant effect on the conveying rate. The number of blades exhibits a noticeable influence, with confidence levels exceeding 80%, while the blade curvature radius has a minimal impact, as its confidence level remains below 80%.

Table 4

Analysis of variance

Indicator	Source of variation	SS	df	MS	F	sig.
Mid-term rate	Variation in blade curvature radius	1.981	2	0.991	0.032	0.969
	Number of blades	270.173	2	135.087	4.346	0.187
	Tangential angle between flow-guiding baffles and conveyor	563.144	2	281.572	9.059	0.099
	Residual	62.166	2	31.083		
Mid-term stability	Variation in blade curvature radius	179.793	2	89.897	0.244	0.804
	Number of blades	1095.177	2	547.589	1.485	0.402
	Tangential angle between flow-guiding baffles and conveyor	508.185	2	254.093	0.689	0.592
	Residual	737.325	2	368.663		

Based on the optimization analysis of the blades and flow-guiding baffles, the conveying system of the calf feeding machine adopts circular-arc blades (with a curvature radius variation of 0°), incorporates 8 blades, and sets the tangential angle between the flow-guiding baffles and the conveyor at 45°.

Structural measurement test of milk replacer conveying device

The test first switched the system to manual mode, selected the "hopper feeding function" on the interface, and utilized load cells installed beneath the agitation mechanism for data acquisition. Collected data were stored in .txt format files. Three discharge trials were repeated. Fig. 7 shows the conveying section of the hopper assembly equipped with circular-arc blades (8 blades) and 45° flow-guiding baffles. Fig. 8 illustrates the agitation mechanism with load cells mounted underneath.

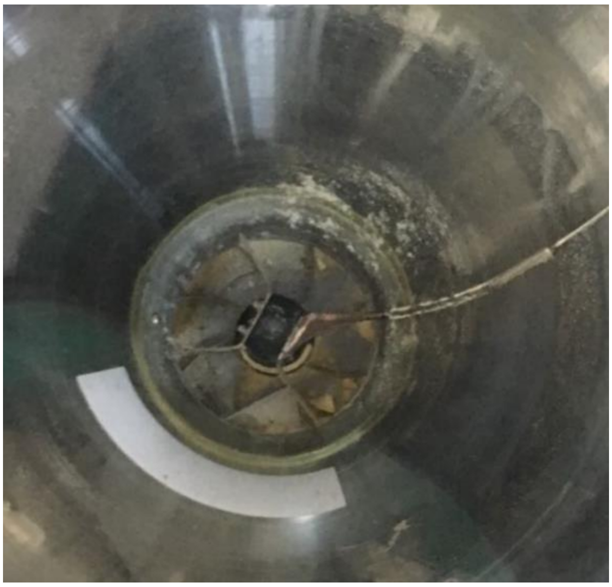


Fig. 7 – Circular-arc-8-blade conveying device with 45° flow-guiding baffles

Fig. 8 – Milk replacer agitation mechanism with load cell

After subtracting the initial weight of the agitation mechanism at 0 s from all data, the processed data were analyzed. The discharge quantity versus time curve is plotted in Fig. 9.

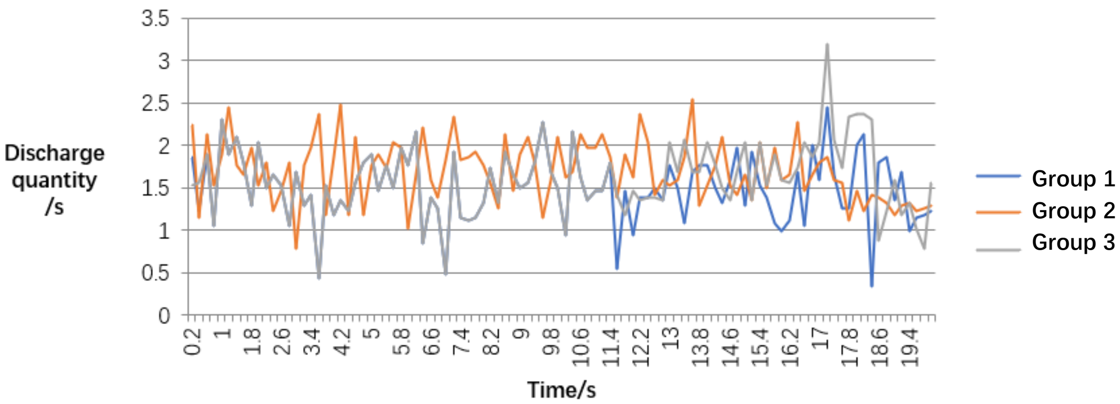


Fig. 9 – Discharge quantity versus time curves for three replicate trials of the feeding mechanism

Based on three replicate trials, the mean value, standard deviation, and operational stability of the discharge quantity are presented in Table 5.

Table 5

Discharge quantity standard deviation analysis table

Trial sequence number	Mean discharge quantity (g/s)	Standard deviation	Operational stability
1	7.50	0.40	73.31%
2	8.48	0.36	75.96%
3	8.01	0.43	71.80%

Table 4 indicates a low standard deviation in discharge quantity, demonstrating high operational stability. The mean discharge rate remains within 7.50 ~ 8.48 g/s, confirming that the feeding mechanism maintains consistent material conveyance during testing. This discharge rate complies with design specifications and ensures feeding continuity.

CONCLUSIONS

(1) Through friction characteristic testing of milk replacer material in the storage device, the internal friction angle was measured as 23.76° and the external friction angle as 23.97°. Based on the frictional characteristics, a scraper-type milk replacer conveying device for calf feeding equipment was designed.

(2) The movement of powder material inside the conveyor was simulated, and tests were performed to analyze the results. The findings show that, regarding the factors influencing the average conveying rate over time, the most important factor is the angle between the flow-guiding baffles and the conveyor, followed by the number of blades, and then the curvature radius of the blades. When it comes to the factors affecting the stability of powder conveying during the same period, the number of blades is the most significant, followed by the angle of the flow-guiding baffles, and lastly the variation in blade curvature radius. At a 0.05 significance level, the tangential angle between flow-guiding baffles and conveyor significantly affects the mid-term rate. The optimal parameters for the calf feeding machine conveying device are: circular-arc blades, 8 blades, and a 45° tangential angle between flow-guiding baffles and conveyor.

(3) Field trials of the conveying device verified discharge stability for the milk replacer system. The mean feeding rate remained within 7.50–8.48 g/s, confirming stable material conveyance by the feeding structure during testing. This discharge rate complied with design requirements and ensured operational continuity.

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