A Cutting Device for Improving the Low-Fluidity Bulk Handling Performance of Belt Conveyor-Type Continuous Unloaders - Basic Design Guideline and Verification of Effect -*

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Abstract

As material-handling equipment for unloading bulk materials such as iron ore and grain from vessels at harbor piers, continuous unloaders play an important role from the viewpoint of handling performance and environmental protection. Among the various types, belt conveyor-type unloaders are required to provide highly versatile handling performance covering low- to high-fluidity bulk materials. When low-fluidity bulk materials are handled, handling performance decreases and electric energy consumption increases because they do not flow easily into a scraping device. For a scraping device consisting of a horizontal screw and a rotary feeder, this paper proposes a cutting device in which multiple rotatable blades are arranged outside the scraping device. It also describes the basic structure and design guideline of the newly proposed cutting device to improve its low-fluidity bulk handling performance. Furthermore, the driving conditions of the cutting device are optimized, and the improvement of the handling performance is verified by experimental analyses using a model manufactured based on the design guideline. Cement, which is a typical low-fluidity bulk with a large angle of repose, is used for experiments. Low-fluidity bulk materials such as coal, converter slag and soybean meal having some different physical properties from those of cement, such as larger particle size, higher bulk density or higher moisture content, are also examined and discussed as materials for digging. The effect of each physical property on the handling performance, as well as the effect of the proposed device and its effectiveness toward stabilization, are also clarified, including the basic design and method of optimization.

Key words: Industrial Machine, Material Handling Equipment, Continuous Unloader, Handling Performance, Cutting Device, Low Fluidity Bulk, Physical Property, Optimum Design, Model Experiment

1. Introduction

As material-handling equipment for unloading bulk materials such as iron ore and grain from vessels at harbor piers, bucket elevator-type or belt conveyor-type continuous unloaders are used very frequently from the viewpoint of unloading performance, environmental protection and energy saving ⁽¹⁾.

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The bucket elevator-type continuous unloader simultaneously digs, scrapes, and transfers cargoes vertically within a vessel using a bucket elevator. Its material-handling capacity, which is expressed by the amount of bulk unloaded per hour, is large, and it is mainly used on large vessels exclusively for single bulk material. The belt conveyor-type unloader transfers bulk to a belt conveyor using a scraping device, which is a combination of a horizontal screw and a rotary feeder placed at the end of a vertical boom, and then from a vertical boom to a horizontal boom. It has a low to medium handling capacity, and is used often at harbors where relatively many types of bulk materials are unloaded.

A proper system should be selected based on the following criteria, taking into consideration the characteristics of bulk scraping and transferring mechanisms: required material-handling capacity, size of vessel, particle size and bulk density of the handled bulk as basic physical quantities, ease of flowing into the scraping mechanism (ease of gravity flow), which varies depending on physical properties, and ease of mechanical forcible flow.

In general small- to medium-scale piers where vessels weighing from a thousand to several tens of thousands dead weight tons (DWT) anchor, the quay wall has a smaller load-carrying capacity than that of the piers exclusively for large vessels, and there is high demand for unloader types having small to medium material-handling capacity of 600 to 800 t/h. In such case, relatively light-weight belt conveyor-type continuous unloaders are used in many cases, and they are required to provide highly versatile material handling performance covering from low- to high-fluidity bulk materials. In the case of low-fluidity bulk which will not flow into a scraping device easily, material-handling capacity may decline, or handling itself may become difficult, causing serious problems. To avoid such problems, bulldozers or wheel loaders are used inboard in the initial stage of the unloading work. However, the actual material-handling capacity is determined by the capacity of the machines used for the inboard work, and it becomes lower than the basic material-handling capacity of the unloader when high-fluidity bulk materials are handled without inboard work (hereinafter referred to as the nominal material-handling capacity). The material-handling efficiency, which is expressed by the ratio of actual material-handling capacity to the nominal material-handling capacity, could be as low as 25 to 50%. Consequently, technologies for improving material-handling performance, such as the actual low-fluidity bulk handling capacity and the power consumed by the handling operation, are strongly demanded from the viewpoints of economy and energy saving.

Previous studies on the bulk handling performance of continuous unloaders include: a theoretical analysis of bulk digging resistance by the distinct element method for bucket elevator-type unloaders; a study that has clarified the relation between the traveling route of a digging bucket and the digging resistance ⁽²⁾ ⁽³⁾; and a study that has analyzed the material-handling control method for adjusting the bucket traveling speed and the digging depth to ensure quantitative material-handling performance, by simulation and powder mineral ore digging experiments ⁽⁴⁾. However, there has been no research on belt conveyor-type unloaders, which handle many types of bulk materials, in order to create a system for improving the low-fluidity material-handling performance, and to define its structure, design guideline and driving conditions.

First, this paper outlines belt conveyor-type continuous unloaders, and then describes the basic structure and design guideline of a cutting device newly proposed to improve low-fluidity bulk handling capacity, for a scraping device consisting of a horizontal screw and a rotary feeder.

Next, the optimized driving conditions of the cutting device and the improvement in material-handling performance are verified by experimental analysis using a model created based on the basic design guideline, as described in Section 3.2. Cement, which is a typical low-fluidity bulk with large angle of repose, was used as the bulk material to be handled.

Low-fluidity bulk having some different physical properties from those of cement such

as larger particle size, higher bulk density or higher moisture content, coal, converter slag, and soybean meal are also examined and discussed as materials for digging. The effect of each physical property on the handling performance as well as the effect of the proposed device and its stability, are also clarified, including basic design and method of optimization.

2. Outline of belt conveyor-type continuous unloaders

Figure 1 shows the appearance of a belt conveyor-type continuous unloader, which consists of a scraping device, vertical boom, horizontal boom, legs, etc. The bulk within a hold of a vessel is scraped with the scraping device, transferred vertically or horizontally on a belt conveyor installed within the booms, and then transferred to land storage facilities. By swinging, derricking of the booms, and slewing or travelling of the main body operation, the position of the scraping device is changed in order to handle bulk materials.

Figure 2 shows the details of the scraping device, which consists of a horizontal screw, a rotary feeder and a guide plate. The bulk flowing into the scraping device is scraped by the horizontal screw toward the rotary feeder from the direction of its rotating shaft first, and then by the upward movement of the plates of the rotary feeder rotating on the vertical plane, thrown upward along the guide plate, and supplied to a belt conveyor equipped with buckets. The guide plate prevents clogging of bulk by providing sufficient ejection space, and controls the angle of ejection to supply the bulk to the belt conveyor efficiently.

In the case of materials with high gravity flow property such as flour (angle of repose: approximately 30°) and rapeseed (angle of repose: approximately 25°), by inserting the scraping device 1.5 to 2.0m into the cargoes, sufficient amount of bulk flows into the scraping device, and stable and high material-handling capacity is ensured by fixed-point handling, wherein the scraping device is handled at a fixed position ⁽¹⁾. Meanwhile, in the case of materials with low gravity flow property such as cement (angle of repose: approximately 52°) and coal (angle of repose: approximately 47°), the amount of bulk flowing into the scraping device by the similar operation is small and so the material-handling capacity decreases greatly. Figure 2 shows the situation of scraping a bulk material that has low gravity flow property. An effective way to solve this problem is to install a device for cutting the bulk around the scraping device. Specific structures and basic design guidelines of the cutting device are proposed in the next chapter.

Fig.1 Appearance of a continuous unloader

Fig.2 Schematic of a scraping device with a handling state of low fluidity bulk

3. Basic structure and basic design guideline of the cutting device

3.1 Basic structure

Figure 3 shows the basic structure of the proposed cutting device. Multiple rotatable blades are arranged, on the outside of the scraping device, about the vertical Z-axis passing through the origin as shown in Fig. 3. The cutting device is moved continuously in the horizontal direction within the hold of a vessel while the blades are rotating; as the device

cuts the bulk, the amount of the bulk flowing into the scraping device is increased, thus improving the material-handling capacity of the unloader.

The cutting device is moved horizontally by traveling operation of the entire unloader, slewing operation of the horizontal boom, and swinging operation of the vertical boom shown in Fig. 1. Each operation is selected in accordance with the movable range of the device defined based on the size of a vessel and the amount of materials remaining in its hold.

Fig.3 Appearance of a proposed cutting device

3.2 Basic design guideline

3.2.1 Function requirement

The cutting device described in Section 3.1 must have the following functions: efficient cutting bulk of the amount equivalent to the nominal material-handling capacity of the unloader, supplying the bulk to the scraping device with minimizing temporal variation of its. Consequently, stable material-handling efficiency is ensured with minimum energy consumption of the cutting device. The cutting device must also minimize fluctuations in handling performance when the traveling direction of the cutting device changes or for the bulk materials having different flow properties. To achieve these functions, the basic concept of determining the specifications of the blades and the driving conditions of the device are discussed in the next section.

3.2.2 Specifications of the blades

The specifications of the blades, such as shape, dimensions, and arrangement, must be determined so as to achieve the required functions described in Section 3.2.1. Specifically, the height H_{Bt} , inner diameter D_{Bti} , outer diameter D_{Bto} of the blades and the gap between them S , as well as the rake angle α and clearance angle β at the tip of the blades and the number of the blades n must be determined, as described below.

(1) Height

The height of the blades H_{Bt} shown in Fig. 3 (a) is determined by the height for cutting the bulk H and the difference in elevation of tongue-and-groove surface of the bulk to be cut Δh . The cutting height H is set from the bottom end of the horizontal screw, which transfers bulk materials horizontally, to the position equal to the diameter of the horizontal screw D_{HS} . Cutting state becomes efficient if the actual material-handling capacity mostly equal to the nominal material-handling capacity of the unloader is provided under these conditions. Meanwhile, the difference in elevation of tongue-and-groove surface Δh is generated by the displacement of the scraping device in the vertical direction resulting from the elastic behavior of the vertical and horizontal booms, which occurs during material-handling operation of the unloader such as swinging and slewing. Since this value is approximately 0.2 times of the diameter of the horizontal screw D_{HS} or smaller from the measurement example for a real machine, the height of the blades H_{Bt} is set by the following equation:

$$H_{Bl} = \delta_{BU} D_{HS} \quad (1)$$

where, δ_{BU} is a coefficient of surface unevenness, expressed by the ratio of H_{Bl} to D_{HS} . As the δ_{BU} value, 1.2 is used for this unloader structure. For different structures, however, displacement in the vertical direction due to elastic behavior must be taken into consideration.

(2) Inner/outer diameter and gap

By minimizing the inner diameter of the blades D_{Bli} without interfere with the scraping device, the cut bulk can be supplied to the scraping device efficiently. It is therefore necessary to select the minimum value while taking manufacturing accuracy into consideration, on condition that the value is larger than the width across corner of the horizontal screw.

The outer diameter of the blades D_{Blo} is set so that the following formula is satisfied:

$$D_{Blo} \geq D_{Bli} + 2S \quad (2)$$

where, D_{Bli} is the inner diameter of the blades, and S is the gap between blades expressed as the horizontal distance between the rear edge of blade i and front edge of blade $i+1$ shown in Fig. 3 (c). The larger the outer diameter of the blades D_{Blo} , the larger the rotating torque, which is the product of the radius of rotation of the blades and the cutting resistance to each blade. Consequently, it is desirable that D_{Blo} be $D_{Bli} + 2S$ or larger and close to this value.

The gap between blades S must not allow particles of the bulk to be cut to become clogged in the gap, and must also satisfy the conditions for the particles to flow inside the cutting device efficiently. From experimental observations, since the state of inflow of particles cut by the tip of the blades through the gap was found to be mostly equal to falling, it is considered to be close to flow by gravity. In addition, as shown in Fig. 3 (c), the shape of inflow port formed by the gap, vertical line segment of the front end of blade $i+1$, and that of the rear end of blade i is a rectangle. It was therefore concluded that the gap S should be such as to exceed the width limit allowing the particles to flow out of the rectangular slit at the bottom of the flat-bottom container housing the particles under the force of gravity. Langmaid, et al. conducted gravity flow experiments using silica sand, and obtained the following experimental equation for the bulk outflow limit width s from a rectangle slit ⁽⁵⁾:

$$s/Dps = 1.8 + 0.038(\phi s/\phi v)^{1.8} \quad (3)$$

where, ϕs is the coefficient of shape of surface area of particles, ϕv is the coefficient of volumetric shape, and Dps is the equivalent specific surface diameter.

The low fluidity bulk analyzed in this paper, where particles are not artificially generated, is considered to satisfy the condition $\phi s/\phi v = 10$ ⁽⁶⁾, which is quite often satisfied by particles obtained by crashing minerals. From equation (3), the outflow limit width $s = 4.2 Dps$. The equivalent specific surface diameter Dps can be used to calculate the bulk outflow limit width s , assuming that the count median diameter of the bulk particles can be used, and that value is regarded as the gap between blades S . The validity of this concept will be verified in Chapter 6.

(3) Rake angle and clearance angle

The rake angle α of the tip of the blade $i+1$ shown in Fig.3(c) is the angle formed by the synthesized velocity V_b between the traveling speed of the entire cutting device V_m and the circumferential velocity of the blades V_c and the inner surface of the blade. The clearance angle β is the angle formed by V_b and the tangential line of the outer surface of the blade $i+1$ at the tip point of the blade. These angles are determined as follows, with reference to the papers on the cutting mechanism of the dirt discharge plate using dry silica sand by Hatamura, et al. ⁽⁷⁾⁽⁸⁾. In those papers, the effect of cutting angle (rake angle in this paper) and the depth on the magnitude and direction of cutting resistance was examined by

experiments using the silica sand having a count median diameter of 0.2 mm, bulk density of 1.46 t/m^3 , and the angle of internal friction of 38° . The cutting resistance to the dirt discharge plate was confirmed to decrease in the range where the rake angle $\alpha \leq 30^\circ$ and the clearance angle $\beta > 0^\circ$. Since the physical properties of silica fall within the physical property range of the bulk for the analysis of this paper shown in Table 1, the rake and clearance angles are set so that the above conditions ($\alpha \leq 30^\circ, \beta > 0^\circ$) are satisfied.

(4) Number of blades

The number of blades n is set so that the inner/outer diameter conditions shown by formula (2) and the rake angle α and clearance angle β conditions described in the previous Section (3) are satisfied. As the number of blades n increases, the rake angle α shown in Fig. 3 (c) increases, and under the conditions of rotating speed of the blades and the traveling speed of the cutting device to be described in Section 6.1.1, the rake angle α become 30° or larger if the number n exceeds 10. Meanwhile, the smaller the number of the blades n , the smaller the clearance angle β , and when the number n is 2, the clearance angle β become smaller than 0° . Therefore, it is appropriate to set the number n to 4, 6, or 8 in view of the ease of arranging the blades during manufacture, because they can be arranged symmetrically with respect to the X- and Y-axes. Furthermore, when the number n is 4, the clearance angle may become smaller than 0° if the traveling speed of the cutting device V_m becomes higher, and the higher the number n , the more continuously bulk can be supplied to the scraping device. Consequently, 8 blades are selected for the device to be analyzed in this paper, as shown in Figure 3 (b).

3.2.3 Driving conditions of the cutting device

The driving conditions include the rotating speed of the blades N and the traveling speed of the entire cutting device V_m . The relation between these parameters and the cutting thickness t and cutting quantity Q_{cd} of the relevant device is clarified, and then the concept of optimizing the driving conditions is described below.

(1) Rotating speed of the blades

The rotating speed of the blades N (rpm) is related to the thickness t (m) of bulk to be cut by a blade shown in Fig.3(c). Under the conditions where the traveling speed V_m (m/min) and the number of blades n (pieces/rotation) are fixed, the lower the rotating speed of the blades N , the larger the cutting thickness t . This relation is represented by the following equation:

$$t = V_m / nN \quad (4)$$

Note that t found by this equation is the value obtained at the leading point in the traveling direction of the cutting device. If the cutting thickness t is large, the volume of bulk cut by individual blades becomes large, and the state of inflow of bulk through the gap S (m) between blades described in 3.2.2 (2) changes. To assess the effect of this change on the material-handling performance, the ratio of the cutting thickness t , which varies depending on the rotating speed of the blades N , to the gap between blades S is defined as incision rate τ (%), which is represented by the following equation:

$$\tau = 100 t / S \quad (5)$$

Optimization of the rotating speed of the blades N will be discussed using this index in Chapter 6.

For the discussion in Section 6.1.1, the equation expressing the result of combining equation (4) and (5) is shown below:

$$\tau = 100 V_m / nNS \quad (6)$$

(2) Traveling speed of the cutting device

The higher the traveling speed V_m of the cutting device, the larger the cutting quantity per unit time Q_{cd} (t/h) of the relevant device. The average cutting quantity Q_{cd} can be calculated by the following equation using the cutting cross-sectional area, which is the product of cutting height H (m) shown in Fig. 3 (a) and the outer diameter of the blades D_{Blo} (m) shown in Fig. 3 (b), bulk density γ (t/m³) of the bulk material, and the traveling speed of the cutting device V_m (m/min):

$$Q_{cd} = 60HD_{Blo}\gamma V_m \quad (7)$$

To identify the optimum cutting quantity of the cutting device Q_{cd} against the nominal material-handling capacity of the unloader, the results of experiments conducted to examine the effect of the traveling speed V_m on the material-handling performance will be shown in Chapter 6, and the optimization of the traveling speed will be discussed. The amount of bulk flowing in from the sides of the cutting cross-sectional area described previously may vary depending on the angle of repose, but since the amount that reaches the scraping device is not known, its effect is not taken into consideration in equation (7) in calculating the cutting quantity Q_{cd} .

4. Bulk to be dug and experimental setup

4.1 Bulk to be dug

Various low-fluidity bulk materials high in one of the following parameters were selected as the bulk to be dug: [1] angle of repose as an index of resistance to gravity flow, which largely determines the inflow into the scraping device, [2] angle of internal friction and angle of wall friction as indexes of resistance to mechanical forcible flow such as cutting and scraping, [3] particle diameter and true density as basic physical quantities related to the movement of individual particles and resistance to deformation of the particles of bulk materials during the period from being broken down by blades to being supplied to the scraping device, and also the moisture content, which affects the magnitude of binding force between particles, and [4] bulk density related to the material-handling capacity. Based on these, the effect of physical properties on the material-handling performance is discussed in Chapter 6.

Figure 4 shows the particle size distribution of the bulk materials dug, and Table 1 lists their physical properties. Except for true density, samples were extracted for measurement at the time of experiment. Figure 4 shows that the particle size of cement was the smallest, namely 0.1 mm or smaller, followed by that of converter slag, soybean meal, and then coal. The particle size of the coal ranged from several mm to approximately 20 mm. As shown in Table 1, cement had the largest angle of repose and angle of wall friction, 52° and 28.8°, respectively. Coal had the largest count median diameter, 11 mm. Converter slag had the largest bulk density, 1.78 t/m³, and soybean meal had the largest moisture content, 10.1%.

Fig.4 Cumulative size distribution of bulk materials used for experiments

Table 1 Properties of bulk materials used for experiments

Item	Cement	Coal	Converter slag	Soybean meal
Count median diameter (mm)	0.016	11	0.75	1.07
Bulk density (t/m ³)	1.6	0.75	1.78	0.65
True density*1 (t/m ³)	3.2 ⁽⁹⁾	1.4 ⁽¹⁰⁾	3.5 ⁽¹¹⁾	1.3 ⁽¹²⁾
Moisture content (%)	0.24	8.2	5.94	10.1
Angle of repose (°)	52	47	46	39
Angle of internal friction (°)	34.7	39	39.4	36
Angle of wall friction*2 (°)	28.8	6.8	19.1	18

*1: Literature data *2: Material: SS400

4.2 Experimental setup

Figure 5 shows the outline of the experimental setup, which consists of a cutting device, scraping device, belt conveyor, hopper, supporting columns and a movable carriage for carrying bulk materials. The horizontal traveling speed of carriage can be varied.

Table 2 shows the basic specifications of this setup. The setup was assumed to be a compact model having small material-handling capacity, and two types having different dimensions and material-handling capacities of the scraping device were used depending on the particle size of the bulk material to be dug.

For cement, which had smaller particle size in the particle size distribution shown in Fig. 4, model No. 1, which had smaller dimensions, was used. The nominal material-handling capacity of the scraping device of the model was 22 t/h under the conditions for handling cement having bulk density of 1.6 t/m^3 . Sufficient distance with respect to the outflow limit width s of the particles shown in Section 3.2.2 (2) was ensured, with the outer diameter of the blades D_{Blo} set at 0.51 m, and the gap between blades S as 30 mm. Consequently, the effect of clogging of bulk materials in gaps was eliminated, and so underlying effect of the cutting device on low-fluidity bulk materials could be verified. In addition, with model No.1, a vibrator was installed in the carriage so that the bulk particles became hardened and packed densely in the carriage.

For coal, converter slag, and soybean meal, whose particle sizes were larger than that of cement, model No.2, which had larger dimensions, was used. The nominal material-handling capacity of the scraping device was 51 t/h under the conditions for handling coal having bulk density of 0.75 t/m^3 . The outer diameter of the blades D_{Blo} was set at 0.9 m, and the gap between the blades S was set at 50 mm, more than four times larger than the count median diameter of coal of 11 mm. This value was close to the outflow limit width s of particles, and its effect will be discussed in Chapter 6. In addition, model No. 2 had a mechanism for rotating and fastening the cutting device, scraping device and belt conveyor collectively about the vertical axis so that the horizontal traveling direction of the cutting device could be changed.

Fig.5 Experimental setup (Model No.2)

Table 2 Specifications of the experimental setup

	Item	Model No.	
		1	2
Cutting device	Outer diameter of blade, D_{Blo} (m)	0.51	0.9
	Gap between blades, S (mm)	30	50
	Cutting height, H (m)	0.22	0.4
	Rotating speed of blades, N (rpm)	15~32	17
	Traveling speed, V (m/min)	1.0~2.5	0.8~3.2
	Motor power (kW)	2.2	2.2
Scraping device	Outer diameter (m)	0.215	0.4
	Width (m)	0.066×2	0.105×2
	Rotating speed (rpm)	340	256
	Outer diameter (m)	0.215	0.34
	Width (m)	0.09×2	0.15×2
	Rotating speed (rpm)	340	256
Nominal Scraping capacity (t/h)		22 *1	51 *2

*1: at bulk density : $1.6 \text{ (t/m}^3\text{)}$ *2: at bulk density : $0.75 \text{ (t/m}^3\text{)}$

5. Experimental method and method of assessing material-handling performance

5.1 Experimental method

The carriage carrying bulk materials was made to travel to simulate the horizontal

traveling of the cutting device. The actual material-handling capacity of the unloader Q_a and the power consumed to rotate the blades P_{Bl} were respectively measured by a scale installed in the hopper of the experimental setup and by a clamp-type wattmeter mounted to the power cable of the blade driving motor, while the actual material-handling capacity of the scraping device was measured. Measurement was conducted either once or three times, in which case the average value was used for the consideration.

Figure 6 shows the horizontal traveling direction of the cutting device used for the experiment. The point of intersection between the vertical axis (Z-axis), which is the center of rotation of blades, and the horizontal axis (X-axis), which is the center of rotation of the rotary feeder, was regarded as the origin, and the minus direction of the Y-axis, which passes through this origin and crosses orthogonal to the Z-axis and the X-axis, was regarded as the forward direction. The forward direction is the direction of visual checking from the front when viewed from the operator's seat (minus side in the Y direction in Fig. 1). Transfer at 45° from the forward direction clockwise on the horizontal plane was defined as the diagonal direction, transfer at 90° was defined as the sideward direction, and transfer at 180° was defined as the backward direction. The forward and backward directions are those of swinging operation, the diagonal direction is the direction of slewing operation, and the sideward direction is the transfer direction in the traveling operation. The experiments were conducted by selecting one of these directions.

Fig.6 Traveling direction of cutting device for experiments

5.2 Method of assessing the material-handling performance

The effect of the cutting device to improve the material-handling performance of the unloader was examined and verified with using the material-handling efficiency of the unloader η_{un} (%), which is expressed as the ratio of actual material-handling capacity of the unloader Q_a (t/h) to the nominal material-handling capacity Q_n (t/h), as shown in the following equation:

$$\eta_{un} = 100 Q_a / Q_n \quad (8)$$

Furthermore, the effective capability rate of the cutting device η_{cd} (%) represented by the following equation was also used as an index for assessing the optimum driving condition of this device:

$$\eta_{cd} = 100 Q_a / Q_{cd} \quad (9)$$

where, Q_{cd} is the cutting quantity per unit time (t/h), and is calculated using equation (7) assuming that bulk materials do not flow into the scraping device from the sides of cross-sectional area of the cutting device described in Section 3.2.3 (2).

As another index for assessing the material-handling performance, the electric energy consumption given by the equation below was used:

$$P = 1000 P_{Bl} / Q_a \quad (10)$$

where, P_{Bl} is the electric power consumption of the blades (kW), and Q_a is the actual material-handling capacity of the unloader (t/h). This P (Wh/t) is the electric energy consumed by the cutting device per ton of cargo handled by the unloader.

6. Results of experiment and discussion

6.1 Optimization and effect of driving conditions of the cutting device

6.1.1 Optimization of driving conditions

(1) Rotating speed of blades N

Figure 7 shows the relation between the effective capability rate of the cutting device η_{cd} and the incision rate τ found by equation (6) using the rotating speed of the blades N for cement. The traveling speed of the cutting device V_m was set at $V_m = 2.1$ m/min. So the cutting quantity per unit time Q_{cd} in equation (7) became equal to the nominal material-handling capacity of the unloader Q_n . Where, Q_n is the record capacity of compositions of the unloader, such as scraping device or belt conveyor, in case of the representative and high-fluidity bulk materials handling condition⁽¹³⁾. Therefore, nominal scraping capacity shown in Table 2 is used for Q_n hereinafter. The traveling direction of the cutting device was set to forward direction defined in Section 5.1.

From Fig. 7, as the incision rate τ increases, the effective capability rate η_{cd} also increases, probably because of the following reasons: the lower the rotating speed of the blades N and the larger the cutting thickness t in equation (4), the larger the amount of cement to be cut by individual blades. Consequently, the amount of cement flowing into the cutting device due to breakdown of the sedimentary cement layer through the gap S between blades shown in Fig. 3 (c) increases. Furthermore, a large amount of cement exists at the inflow port formed by the gap S and the vertical line segment of the front and the rear ends of the blades, and the amount of cement forcibly pressed into the device increases, thereby increasing the actual material-handling capacity. When τ becomes 40% or higher, η_{cd} exceeds 80%.

Figure 8 shows the relation between the electric energy consumption P of the cutting device per ton handled by the unloader and the incision rate τ . Electric energy consumption P becomes the minimum when the incision rate τ is approximately 40%. The reason why the electric energy consumption P increases when τ is larger is that the elastic reactive force acting on the tip of the blades from the sedimentary cement layer which exist densely in the gap S between blades increases because the rotating speed of the blades N is low and the cutting thickness t in equation (4) is large. Another reason is that the contact area between the cement and the outer surface of the blades shown in Fig. 3 (c), thus increasing friction. The reason why the electric energy consumption P increases when τ is smaller is that the number of times of generation of elastic reactive force acting on the tip of the blades per unit time increases because the rotating speed N increases and the number of cuttings per unit time increases.

Based on the above consideration, the rotating speed of the blades N that makes the incision rate τ approximately 40% is considered to be the optimum driving condition for achieving the effective capability rate η_{cd} of 80% or higher of cement and minimizing

Fig.7 Effective capability rate of the cutting device η_{cd} for cement in model No.1

Fig.8 Electric energy consumption P of the cutting device for cement in model No.1

electric energy consumption P .

(2) Traveling speed V_m

Figure 9 collectively shows the relation between material-handling efficiency of the unloader η_{un} , or effective capability rate η_{cd} , and the traveling speed V_m of the cutting device for cement. The rotating speed of the blades N was adjusted depending on the traveling speed V_m so that the incision rate τ described in the previous section became approximately 40%. The traveling direction was set to forward direction.

As shown in Fig. 9, the material-handling efficiency η_{un} increases with the increase of the traveling speed V_m , and at the traveling speed at which the cutting quantity per unit time Q_{cd} becomes equal to the nominal material-handling capability Q_n ($V_m = 2.1$ m/min.) or higher, the material-handling efficiency η_{un} exceeds 80%. Meanwhile, the effective capability rate η_{cd} decreases slightly with the increase of the traveling speed V_m . The reason for this is as follows: if the traveling speed increases, the amount of cutting increases, but the amount of bulk materials left behind the traveling direction without being scraped also increases.

Figure 10 shows the relation between the electric energy consumption P of the cutting device per ton of material handled by the unloader and the traveling speed V_m . The electric energy consumption P surges when the traveling speed V_m at which the cutting quantity Q_{cd} equals the nominal material-handling capacity Q_n is exceeded. The reason for this is as follows: as a result of increase in the rotating speed of the blades N , which is interlocked with the traveling speed V_m , the circumferential component R_c of the reaction force R generated when the cement is scraped on the inner surface of the blades shown in Fig. 3 (c) increases, thus increasing the rotating torque of the blades. The gray arrow mark in Fig. 3 (c) represents the force applied by bulk materials to the blades.

From the above consideration, when the traveling speed V_m is set so that the cutting quantity per unit time Q_{cd} becomes equal to the nominal material-handling capacity Q_n , the material-handling efficiency of the unloader η_{un} and the effective capability rate of the cutting device η_{cd} both become 80% or higher, and at the same time, an excessive increase in electric energy consumption of the cutting device P can be suppressed.

Fig.9 Material - handling efficiency η_{un} and Effective capability rate of the cutting device η_{cd} for cement in model No.1

Fig.10 Electric energy consumption P of the cutting device for cement in model No.1

6.1.2 Effect of the cutting device

(1) Material-handling efficiency

If the driving conditions, namely the rotating speed of the blades N and the traveling speed of the cutting device V_m , are optimized using the method described above, the material-handling efficiency of the unloader η_{un} can be improved to 80% or higher. Compared to the actual measurement examples of 25 to 50% for inboard work using bulldozers, these driving conditions represent a significant improvement in efficiency.

(2) Electric energy consumption

The electric energy consumption per ton of material-handling amount of the unloader necessary to improve the low-fluidity bulk handling efficiency will be compared when using this cutting device and inboard work using a bulldozer. As shown in Fig. 10, the electric energy consumption of the cutting device P is approximately 7.7 Wh/t, the power necessary for the horizontal moving of this device in traveling operation is approximately 62.5 Wh/t, and the sum of these values necessary for cutting operation is 70.2 Wh/t. Meanwhile, when a bulldozer (rated power: 55 kW) generally used for unloaders having a nominal material-handling capacity of 600 t/h is used, the electric energy consumption for achieving operation rates of 70% and material-handling efficiency of the unloader η_{un} of 50% is approximately 129 Wh/t. Thus, when using this cutting device, the electric energy consumption per ton of material-handling amount of the unloader was decreased by approximately 45% compared with inboard operation of the bulldozer.

From these results, the cutting device proposed in Chapter 3, its basic design guideline, and its optimized driving conditions greatly improves the efficiency of handling low-fluidity bulk materials without increasing the electric energy consumption, unlike when using a bulldozer. But, for long boom type unloader, it is necessary to check unstable vibration problem due to the torsional torque and related sideward force acting on the vertical and horizontal boom generated by attaching the cutting device.

In the following sections, these driving conditions are used and confirmed the applicability of those to various bulk materials other than cement, by showing the material-handling efficiency of the unloader and the effective capability rate of the cutting device.

6.2 Effect of the traveling direction of the cutting device on material-handling performance

The traveling direction of the cutting device may affect the material-handling performance. Experiments were conducted using coal, which is low in fluidity after cutting because it has a large particle size and relatively high angle of internal friction and moisture content, thus greatly affected by the traveling direction, as the target of digging. Model No. 2 was used, in which the traveling direction of the cutting device shown in Fig. 6 can be set.

Table 3 collectively shows the effective capability rate η_{cd} and the electric energy consumption of the cutting device P as well as the actual material-handling capacity Q_a and the material-handling efficiency of the unloader η_{un} . The values in the parentheses are the ratio of the value in each traveling direction to the average value (the rightmost value in the table) expressed as a percentage. The actual material-handling capacity of the unloader Q_a was the highest in the sideward direction, and the lowest in the backward direction. The actual material-handling capacity Q_a in the backward direction was approximately 17% lower than the average value of each traveling direction. Regarding the material-handling efficiency of the unloader η_{un} and the effective capability rate of the cutting device η_{cd} also, the backward direction exhibited the lowest values. The electric energy consumption of the cutting device P was approximately 27% higher than the average value, in the backward condition where the actual material-handling capacity Q_a was the lowest.

Such fluctuation in material-handling performance depending on the traveling direction of the cutting device is considered to be due to the difference in the way in which the coal is scraped depending on the traveling directions. The reason why the material-handling performance is high in the sideward direction is as follows: even though the scraping width W_s of the scraping device in the sideward direction is narrower than that in the forward direction W_f , coal reaches behind the traveling direction of the cutting device in a flowing form shown by the dotted line in Fig. 5 (c), and is recovered by the horizontal screw b installed at that position, which increases the actual material-handling capacity Q_a .

The reason why the material-handling performance in the forward direction is high,

following the sideward direction, is that a large amount of coal can be scraped in positions in front of the traveling direction of the cutting device because the width of the scraping device W_f described above is wide. The approach to determining the gap S described in Section 3.2.2 presents no problems in practice because the material-handling efficiency of the unloader η_{un} and the effective capability rate of the cutting device η_{cd} exhibited values close to 80%, similar to that of cement.

The reason why the material-handling performance is lower in the backward traveling direction of the cutting device is discussed below. Figure 11 is a side view showing the state of scraping of bulk materials in the backward direction as well as the improved structure, which will be described later. When the cutting device travels backward, the amount of bulk materials flowing into part D at the bottom of the guide plate shown in Fig. 11 decreases, and the amount of bulk materials splashed by the rotary feeder at that position increases. As a result of this missed scraping, the actual material-handling capacity Q_a decreases even though the scraping width in the backward direction shown in Fig. 5 (c) is the same as that in the forward direction W_f , causing a low material-handling performance.

Table 3 Experiment results of handling performance for coal with varying the traveling direction in model No.2

Item	Traveling direction(θ deg)				Average
	Forward (0°)	Diagonal (45°)	Sideward (90°)	Backward (180°)	
Material-handling capacity Q_a (t/h)	40.0 (102.3)	38.6 (98.7)	45.2 (115.6)	32.4 (82.9)	39.1
Material-handling efficiency η_{un} (%)	78.4	75.7	88.6	63.5	76.6
Effective capability rate of the cutting device η_{cd} (%)	77.2	74.4	87.1	62.5	75.3
Electric energy consumption of the cutting device P (Wh/t)	25.0 (91.1)	29.2 (106.4)	20.6 (75.0)	34.9 (127.3)	27.4

Fig.11 Bulk handling condition in the case of backward traveling of a cutting device with improved configuration

6.3 Method of decreasing the fluctuation and improving material-handling performance and its effect

To suppress the amount of materials that cannot be scraped by the horizontal screw and the rotary feeder and thus remain in part D at the bottom of the guide plate when the traveling direction was backward as described in 6.2, the guide plate was extended linearly in the vertical direction as shown by the broken line in Fig. 11 up to the bottom end of the blades.

Furthermore, the top edge of the blades was cut diagonally upward to increase the amount of bulk materials to be cut, decrease the cutting resistance of the blades, improve the material-handling efficiency of the unloader η_{un} , and decrease the electric energy consumption of the cutting device P . The height of the origin O_{ci} of the cut shown in Fig. 11 is set so that in blade b , which is at the rearmost position in the traveling direction of the cutting device, the angle γ formed by the line segment that passes through the origin O_{ci} and contacts the outer circumference of the rotary feeder and the horizon becomes smaller than the angle of repose of the bulk material. This is based on the concept that the height of the bulk material H_b held by blade b becomes lower than the height of the cut H_c , and consequently the amount of bulk material leaking from the cut can be decreased. In addition, by setting the height of the cut of the blade at the end O_{ce} at the cutting height H , the cutting resistance was decreased, and the width of the cut W_c was made to be approximately one third of the width of the blade W_{bt} to ensure sufficient strength of the blade.

Table 4 summarizes the actual material-handling capacity Q_a and the material-handling efficiency η_{un} of the unloader, and the effective capability rate η_{cd} and the electric energy consumption P of the cutting device. The actual material-handling capacity Q_a in the

backward direction increased by approximately 50% compared to the unimproved structure. The fluctuation range of the ratio of the actual material - handling capacity Q_a in each traveling direction to the average of that Q_a was decreased from approximately $\pm 17\%$ before improvement, to $\pm 10\%$. In addition, with the improved structure, the material-handling efficiency of the unloader η_{un} and the effective capability rate of the cutting device η_{cd} reached 80% or higher in all of the traveling directions of the cutting device, and the electric energy consumption P decreased to 11 - 16 Wh/t. Thus, the material-handling performance was improved.

These results showed that the longer guide plate and the cut on the blades effectively reduced the fluctuation in material-handling performance and improved it.

Table 4 Experiment results of handling performance of coal using improved configuration

Item	Traveling direction(θ deg)				Average
	Forward (0°)	Diagonal (45°)	Sideward (90°)	Backward (180°)	
Material-handling capacity Q_a (t/h)	44.9 (99.6)	42.4 (94.0)	43.4 (96.2)	49.5 (109.8)	45.1
Material-handling efficiency η_{un} (%)	88.0	83.1	85.1	97.1	88.3
Effective capability rate of the cutting device η_{cd} (%)	86.7	81.9	83.7	95.5	87.0
Electric energy consumption of the cutting device P (Wh/t)	12.8 (98.5)	15.3 (117.7)	12.3 (94.6)	11.6 (89.2)	13.0

6.4 Effect of physical properties of dug bulk materials

Table 5 shows the actual material-handling capacity Q_a and the material-handling efficiency η_{un} of the unloader, and the effective capability rate η_{cd} and the electric energy consumption P of the cutting device, for each of the following bulk materials: coal, converter slag and soybean meal. The values for cement are shown for reference as the traveling direction of the cutting device and the cut in the blades were different. The results of each bulk material were obtained under the optimum cutting device driving conditions for cement described in Section 6.1.1. To compare the effect of physical properties under the same conditions, the improved structure described in the preceding paragraph was used for bulk materials other than cement. As the traveling direction of the cutting device, the sideward in traveling operation shown in Fig. 1 was selected because it is often used for material-handling operations due to the ease of horizontal moving.

The actual material-handling capacity Q_a and the material-handling efficiency η_{un} of the unloader were high for converter slag, namely approximately 48 t/h and 94% respectively. The reason why Q_a increased is considered that the bulk density shown in Table 1 was high, thus the weight of bulk to be handled against the volume of scraping by the scraping device and of transferring by the belt conveyor determined by the size of the each device increased. Consequently η_{un} determined by equation (8) also increased.

The effective capability rate of the cutting device η_{cd} of soybean meal was the highest at 86%, followed by coal at 84%. That of the converter slag was the smallest at 78%. The reason why η_{cd} of soybean meal was high is as follows: the angle of repose of soybean meal was the smallest of all the bulk materials as shown in table 1, and consequently the amount flowing from the sedimentary bulk material layer around the cutting device into the relevant device increased, and the actual cutting quantity Q_{cdr} became higher than the cutting quantity Q_{cd} shown in equation (7). Consequently, the amount of bulk materials supplied to the scraping device increased, causing the actual material-handling capacity Q_a , the numerator in equation (9), to increase.

The electric energy consumption of the cutting device P was the largest for soybean meal at 28 Wh/t, followed by converter slag and the coal at 20 Wh/t and 12 Wh/t. From a Hatamura's report⁽⁷⁾ of cutting experiments of silica sand and loam using dirt discharge plate having similar cutting conditions, including rake angle and cutting thickness, the major factors of the cutting resistance to be put on blades which influences P were considered to be the frictional force applied to the contact surface between the blades and the bulk material, or between bulk materials, and the elastic reaction force from the

sedimentary bulk material layer applied to the tip of the blades. The report was conformed as follow: in the case of no-viscous silica sand, the deformation by cutting is in the form of shearing, and so the frictional force becomes larger in a place closer to the tip of the plate. Meanwhile, with viscous loam, the deformation by cutting is in the form of breaking, and so the frictional force is applied evenly over the surface of the plate. In addition, it was shown that the magnitude of frictional force applied to the tip of the plate when loam was handled was 3.5 times higher than that of silica sand when the cutting angle was 30° . Based on these findings, in the case of soybean meal, which exhibits viscous property because it has a high moisture content and relatively small particle size and also is an organic material, frictional force was applied over the entire surface of the blades, causing the electric energy consumption P to increase. The reason why the electric energy consumption P of converter slag was higher than that of coal, even though both are non-viscous, is that the angle of wall friction of the converter slag shown in Table 1 was approximately 2.8 times higher than that of coal. The electric energy consumption P of the cement, which was presented as a reference, was the smallest because it was low in moisture content, was non-viscous, and its particle size was extremely small. Consequently, a shear surface was formed on the bulk material by a small cutting force, and the elastic reactive force from the sedimentary bulk material layer acting on the tip of the blades remained small.

Based on the above consideration, within the scope of the experiment of this paper, the material-handling efficiency of the unloader η_{un} equipped with this cutting device depends on the bulk density of the bulk material, the effective capability rate η_{cd} depends on the angle of repose, and the electric energy consumption P depends on the angle of wall friction, particle size, and the viscous properties of the bulk material, which vary depending on moisture content, etc.

Table 5 Handling performance of various bulk materials

Item	Bulk materials			
	Coal	Converter slag	Soybean meal	Cement
Material-handling capacity Q_d (t/h)	43.4	48.0	42.1	18.5
Material-handling efficiency η_{un} (%)	85.1	94.1	82.5	84.1
Effective capability rate of the cutting device η_{cd} (%)	83.7	78.0	85.6	81.8
Electric energy consumption of the cutting device P (Wh/t)	12.3	20.0	28.3	7.7
Model No. (Traveling direction)	2 (Sideward)			1 (Forward)

7. Conclusion

A cutting device to improve the handling performance of belt conveyor-type continuous unloaders for low-fluidity bulk materials was proposed, and its basic design guideline was presented. The effects of the device and its traveling directions were clarified as well as the method to optimize the driving conditions and the structure. Furthermore, the effect of the physical properties of the bulk material on the material-handling performance was examined, and the effectiveness of the cutting device on various low-fluidity bulk materials was confirmed. The major results obtained within the range of experimental conditions of this paper are summarized below:

(1) The basic structure of the cutting device with multiple rotatable blades arranged on a horizontal plane on the outside of the scraping device, and the basic design guideline that determines the specifications of the blades such as height and inner/outer diameter significantly improve the efficiency of handling low-fluidity bulk material and decrease the electric energy consumption.

(2) As the cutting device driving conditions, the traveling speed of the cutting device V_m was set so that the cutting quantity of the cutting device Q_{cd} became equal to the nominal material-handling capacity of the unloader Q_n , and the rotating speed of the blades N was set so that the ratio τ of the cutting thickness t to the gap between blades S became approximately 40%. Consequently, the material-handling efficiency of the unloader η_{un} and the effective capability rate of the cutting device η_{cd} reached approximately 80% or higher

without increasing the electric energy consumption P per ton of the material handled by the unloader related to the cutting device, compared with the inboard work using a bulldozer.

(3) By extending the length of the guide plate of the scraping device down to the bottom end of the rotary feeder, and forming a cut at the top edge of the blades of the cutting device for coal, which is greatly affected by the traveling direction of the cutting device, the fluctuation range of the ratio of the value of each traveling direction to the average value of the actual material-handling capacity Q_a decreased from approximately $\pm 17\%$ to $\pm 10\%$. In addition, the effective capability rate of the cutting device η_{cd} improved by approximately 16% on average in each traveling direction and the electric energy consumption P decreased by approximately 52% on average. The material-handling performance was thus stable and effectively improved.

(4) The material-handling efficiency of the unloader η_{un} is concluded to mainly depend on the bulk density of the bulk material to be dug, the effective capability rate of the cutting device η_{cd} depends on the angle of repose, and the electric energy consumption P per ton of material handled by the unloader related to the cutting device depends on the angle of wall friction, particle size, and the viscous properties of the bulk material, which vary depending on moisture content, etc.

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