CONVEYING CHARACTERISTICS OF THE SCREW CONVEYOR

by

Yoshiki SANOH, Wasaburo KENGAKU and Motomi OSAKA

Department of Chemical Engineering, The Faculty of Textile Science and Technology, Shinshu University

1. INTRODUCTION

A few theoretical and experimental studies[1,2] have previously been done on the conveying characteristics of the screw conveyor. Only an empirical equation[3] has been proposed for the standard type* horizontal screw conveyor as follows,

$$Q = 60\varphi\frac{\pi}{4}D^2 aN\gamma \quad (kg/hr) \tag{1}$$

In Eq. (1), however, any important factor such as frictional effect between powder and front surface of the screw or powder and inside wall of the conveyor barrel is not taken into consideration. Then Eq. (1) can not be applied to practical use, because it gives much larger value than the real one.

In this work, the observation of the conveying state was carried out in various operational conditions to clear the conveying characteristics. Furthermore, supposing that conveying mechanism of the screw was the same as that of the extruder in the case of high hold-up ratio we compared the theoretical value with observed value.

2. EXPERIMENTAL

An outline of the apparatus used is shown in Fig. 1, and the dimensions of the screws are tabulated in Table 1.

Barrel of the conveyor was made of transparent poly methyl metha acrylate (PMMA). The electro-magnetic vibratory feeder was used for a continuous feeding device, since it had a good accuracy in feed rate and the regulating property.

The screws were made of mild steel with six different pitch ratios.

Toyo-ura sand and granular table salt were used as sample, of which some properties are indicated in Table 2.

While the feed rate of the powder through the feeder to the conveyor

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* The screw possessing the value of (pitch)/(screw diameter) i.e. pitch ratio of 0.75–1.0, is called "standard type".

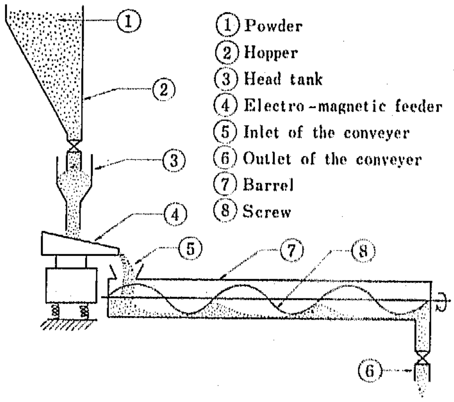

Fig. 1 Experimental apparatus

was kept constant, the hold-up of the powder was maintained at a fixed volume for several minutes. After constancy of the hold-up was confirmed (we regarded that this state was stationary state), the discharge rate in kg/min was measured two or three times at the outlet of the conveyor. Their arithmetic mean was taken as the conveying rate Q.

In order to express quantity of the powder retained in the barrel, the hold-up ratio φ was defined as follows,

Table 1 Dimensions of screw and barrel

Screw	1	2	3	4	5	6
Effective length, (cm)	58	58	58	58	58	58
Diameter, (cm)	5	5	5	5	5	5
Pitch, (cm)	2.2	3.4	5.0	7.4	10	15
Pitch ratio, (-)	0.5	0.7	1.0	1.5	2.0	3.0
Diameter of shaft, (cm)	1.8	1.8	1.8	1.8	1.8	1.8
Clearance, (cm)	0.1	0.1	0.1	0.1	0.1	0.1
Inner dia. of barrel, (cm)	5.2	5.2	5.2	5.2	5.2	5.2

Table 2 Physical properties of the powder

Properties	Toyo-ura Sand	Table salt*
Particle size (μ)	147~295	104~208
Bulk density (g/cc)	1.470	1.156
Repose angle** (°)	30.7	31.3
Coefficient of dynamic friction (-)	0.170	——

* Granular

** Poured angle method

$$\varphi=\left[\begin{pmatrix}\textit{Total Weight of powder}\\ \textit{retained in barrel, kg}\end{pmatrix}-\begin{pmatrix}\textit{Weight of powder in}\\ \textit{dead space, kg}\end{pmatrix}\right]\Big/$$
$$\left[\begin{pmatrix}\textit{Bulk density of}\\ \textit{powder, kg/cm}^3\end{pmatrix}\left\{\begin{pmatrix}\textit{Inner volume of}\\ \textit{barrel, cm}^3\end{pmatrix}-\begin{pmatrix}\textit{Volume of dead}\\ \textit{space, cm}^3\end{pmatrix}+\begin{pmatrix}\textit{Volume of}\\ \textit{screw, cm}^3\end{pmatrix}\right\}\right] \quad (2)$$

3. RESULTS

3.1 Movement of the particulate mass

A movement of the particulate mass was observed through a plastic wall of the barrel. The movement was classified into three different manners depending upon an amount of the hold-up.

Firstly, when both the rotational speed of the screw and the hold-up ratio were low ($\varphi < 0.3$), mass of the powder was transported toward the screw outlet in the following manner. Mass of the powder was divided into the space of each pitch, and each surface of the powder mass inclined to both directions of the screw axis and the rotation. The angle of such inclination was nearly equal to the repose angle of the sample powder.

Secondly, in the case of moderate hold-up ratios, more active movement of the particles was observed. A part of the powder mass rotated with the screw cascading to the bottom. The cascaded powder, which retained without conveying, is called "shaft leakage". Whole mass of the powder was extruded along the screw axis accompanying with "shaft leakage".

Thirdly, in the case of large hold-up ratios, i. e. $\varphi \fallingdotseq 1$, the movement of the individual particle was very little. Almost all of particles rotated with the screw in lower speed than in the screw. As the result, a mass of the powder moved in a loop fashion toward the screw outlet.

3.2 Relationship between Q and φ

In Figs. 2 and 3 the relationship between conveying rate Q and hold-up ratio of the powder φ is plotted in log-log scale. The relation of $\log Q$ and $\log \varphi$ is given as the curve consisted of two or three segment lines. When the pitch ratio is low, the relationship between $\log Q$ and $\log \varphi$ is given in three

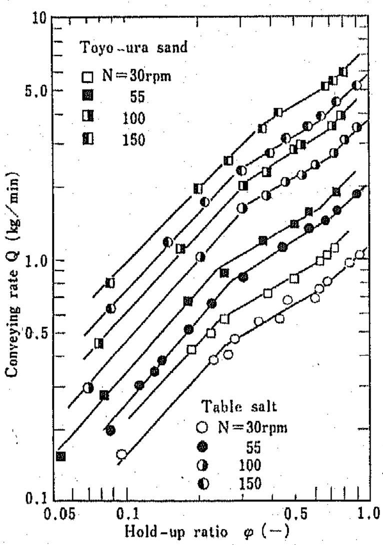

Fig. 2 Influence of φ on Q at a low pitch ratio ($a/D=0.5$)

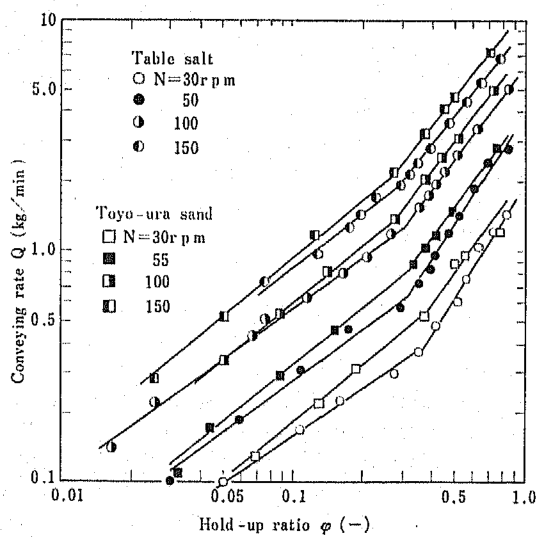

Fig. 3 Influence of φ on Q at a high pitch ratio ($a/D=3.0$)

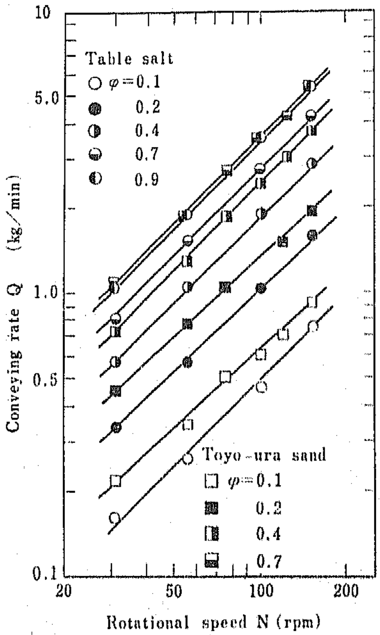

Fig. 4 Relationship between Q and N at a low pitch ratio ($a/D = 0.5$)

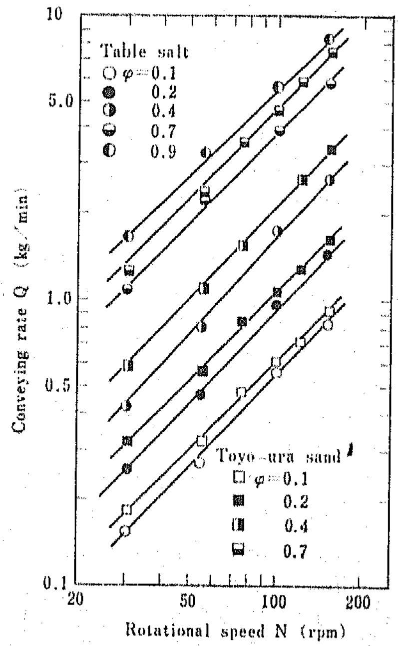

Fig. 5 Relationship between Q and N at a high pitch ratio ($a/D=3.0$)

segment lines, while in two segment ones at high pitch ratio. These relations are recognized in various rotational speeds.

3.3 Relationship between Q and N

The experimental results about influence of rotational speed of the screw N on the conveying rate Q is shown in Figs. 4 and 5. Log Q becomes larger proportionaly with increment of log N. The gradient value of every straight line is about 1, which is seen in various hold-up ratios, pitch ratios and even in different kinds of the powder. Therefore, the conveying rate takes a direct proportion to the rotational speed.

3.4 Relationship between Q and a/D

In order to estimate the relationship between the conveying rate Q and the pitch ratio a/D, the results obtained from such peripheral speeds of the screw as 500, 1,500, 2,000 and 2,500 (cm/min) are plotted in log-log scale. Fig. 6 shows the case of speed of 500 (cm/min). From these plots, the following results were obtained.

(1) The value of Q has the maximum value Q_{max} at a certain value of pitch ratio.

(2) The value of pitch ratio in Q_{max} approaches to 2.0 with increase of hold-up ratio regardless of kind of powders.

(3) The tendency mentioned in (2) also holds at another rotational speed.

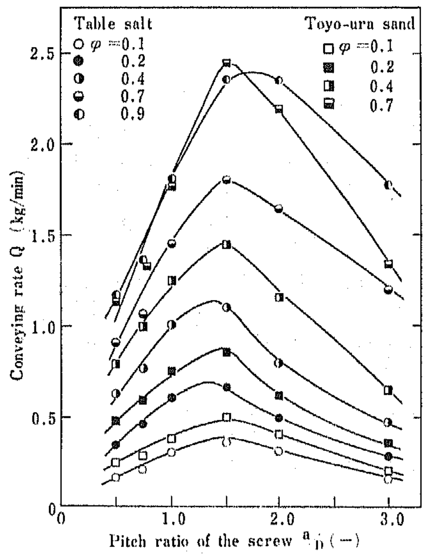

Fig. 6 Relationship between Q and a/D for the peripheral speed of 500 cm/min.

4. DISCUSSION

As mentioned in Section 3.1, a movement of the particles in the screw conveyor is extremely complicated.

Dynamics of a particle in a screw conveyor has been considered by Uematsu[4]. Further, the senior author[5] has observed a movement of the sawing dust in a screw conveyor. However, theoretical and experimental analysis on the movement of the powder mass has not yet been studied sufficiently. In any case, it is impossible to know the relationship between the movement of each particle and the conveying rate of the screw.

In the following discussion, it will be analyzed the relation between macroscopic behaviour of a powder mass and the conveying characteristics.

4.1 Hold-up of the powder

Each segment line in Figs. 2 and 3 corresponds to different conveying manners.

In fact, "shaft leakage" was observed under the condition of $\varphi > 0.3$. In a range of $\varphi < 0.3$ such a phenomenon was not observed. Accordingly the critical point of φ seems to exist nearly at a value of 0.3. Beyond the second critical point in Fig. 2, the amount of "shaft leakage" decreased as hold-up increased. Thus, the conveying manner changed to the same manner as that of an extruder. It may be resulted from the change of the frictional condition between the powder and the screw surface. The value of φ at the second critical point was reduced with increase of pitch ratio, because the extruding action was predominant to the conveying action in the screw conveyor even if the hold-up ratio was small.

4.2 The screw pitch ratio

Theoretically, the conveying rate must be zero when the screw pitch ratio is zero or infinite. So that, the optimum pitch ratio which gives Q_{max} should lie between zero and infinite.* This is confirmed in Fig. 6.

Now, the relation of conveying rate and pitch ratio in the case of $\varphi \fallingdotseq 1$, where a movement of the powder mass is most simple, will be analyzed in the following.

As mentioned in Section 4.1, the conveying manner of the screw under a condition of $\varphi \fallingdotseq 1$ may be analogous to mechanism of an extruder. Supposed that the conveying mechanism of the screw is the same as that of the extruder, the conveying rate will be estimated.

Both theoretical equations of extruding rate proposed by Darnell & Mol[6] and Matsumoto *et al.*[7] show good agreement with the empirical values. Here Darnell's theory will be applied in our case.

Dernell & Mol has proposed the following equation.

$$Q/N = \frac{\pi^2 Dh(D-h)\tan\theta\tan\phi_B}{\tan\theta + \tan\phi_B} \qquad (cm^3/rev.) \qquad (3)$$

where θ is defined as follows,

$$\cos\theta = K\sin\theta + C\ (K\sin\phi_s + C\cos\phi_s) + \frac{2h}{a}(KC\tan\phi_s + E^2)$$
$$+ \frac{hE}{L\mu_B}\cdot\sin\phi_a(E\cos\phi_a + K\sin\phi_a)\,ln\frac{P_2}{P_1} \qquad (4)$$

where

$$K = E(\tan\phi_a + \mu_s)/(1 - \mu_s\tan\phi_a) \qquad (5)$$

Here putting the last three terms of Eq. (4) in M, we get

$$\cos\theta = K\sin\theta + M \qquad (6)$$

For the sake of application of Eqs. (3) to (6) for the extruder to the conveyor, the following assumptions are taken.

(i) Pressure drop between the inlet and the outlet is kept zero [then the last term of the right hand side of Eq. (4) is omitted].

(ii) Coefficient of friction between the powder and the inside of barrel is equal to that between the powder and the screw surface.

(iii) Thickness of the screw flight is negligibly small in comparison with dimensions of the barrel. Then the third term of the right hand side of Eq. (4) may be negligible.

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* Calculation of Eq. (1) does not give the maximum value of Q.

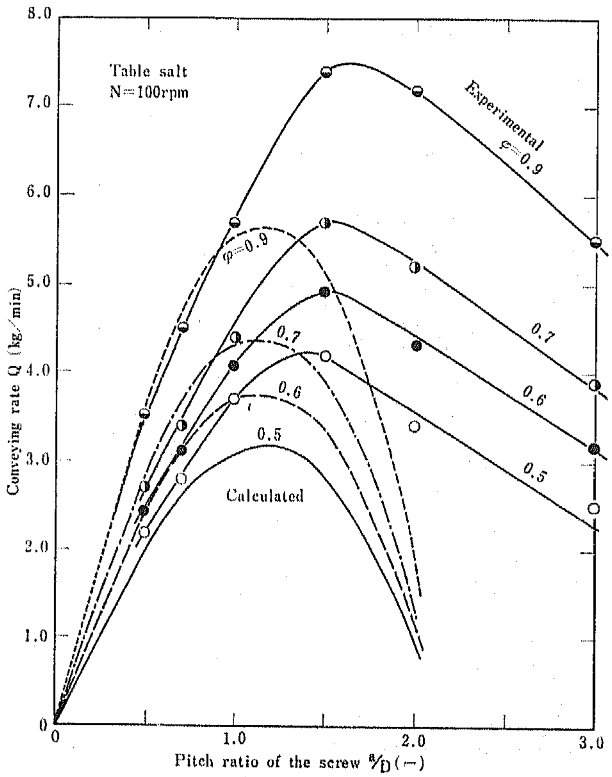

Fig. 7 Comparison of the observed value with the calculated value obtained by using the repose angle.

Based on these assumptions, the conveying equation will be given as follows,

$$Q=\left[\frac{\pi^2 Dh(D-h)\tan\theta\ \tan\phi_B}{\tan\theta+\tan\phi_B}\right]\left(\frac{a-e}{e}\right)N\varphi\gamma \tag{7}$$

and

$$\cos\theta = K\sin\theta + C\,(K\sin\phi_s + C\cos\phi_s) \tag{8}$$

(Calculation 1) The case of making use of repose angle as a coefficient of friction

The conveying rate Q was calculated by using Eq. (7), (8) and the repose angle. The results are shown in Fig. 7. The optimum value of pitch ratio $(a/D)_{opt}$ is considerably smaller than that obtained by the experiments. Further the calculated values of Q do not agree at all with those of the empiricals beyond $(a/D)_{opt}$ as shown in Fig. 7.

(Calculation 2) The case of making use of the coefficient of dynamic friction

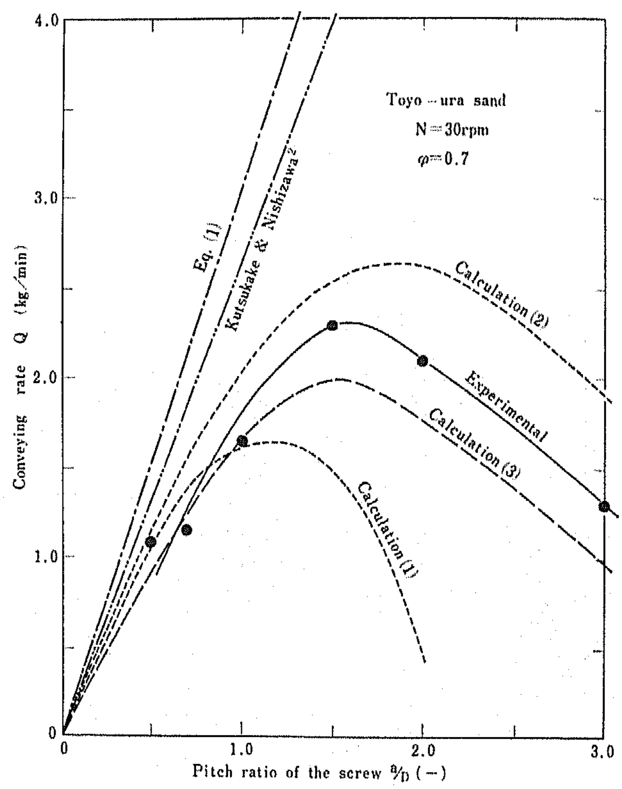

Fig. 8 Comparison of several calculating methods of Q

as a coefficient of friction

In Calculation 1, the frictional property was given by the repose angle. But almost all of the frictional properties of powders in this conveyor may appear under the moving state. Therefore, the coefficient of dynamic friction[8] is more applicable than repose angle. The calculated results are shown in Fig. 8. The values of Q are larger than those obtained by the experiments, in any values of pitch ratios. The theoretical values however showed better agreement with the empirical values than those obtained in Calculation 1.

(Calculation 3) The case when the third term of Eq. (4) is not omitted

Although the width of each screw employed in this work is narrow, the amount of the powder trailed by the screw can not be neglected. Then an estimation was tried concerning Q under a condition including the trailing effect factor. Results obtained are plotted in Fig. 8. Eq. (1) and its modification proposed by Kutsukake & Nishizawa[2] are denoted also in Fig. 8. The calculated values give good agreement with the empirical ones at $a/D<1.0$, though a fairly deviation appears at $a/D>1.5$, especially at $a/D>2.0$. The last Calculation is the most reasonable among the above calculations.

5. CONCLUSIONS

In this paper, the conveying characteristics were analyzed. In the case of large values of φ ($\varphi \fallingdotseq 1$), the conveying mechanism of the screw was supposed to be the same as that of the extruder.

It may be concluded from the results as follows :

(1) The conveying meachanisms depending on the hold-up ratios must be classified into three different manners.

(2) The influence of the rotational speed on the conveying rate is most simple among various factors. Q shows a direct proportion to N.

(3) The optimum pitch ratio in Q_{max} ranges between 1.5 and 2.0.

(4) In the case of large hold-up ratio ($\varphi = 0.7$—1.0), the conveying mechanism of the screw is regarded to be the same as that of the extruder, qualitatively.

ACKNOWLEDGEMENT

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NOMENCLATURE

a	: Pitch of the screw	(cm)
C	: $(D\text{-}2h)/D$	(−)
D	: Diameter of the screw	(cm)
E	: $(D\text{-}h)/D$	(−)
e	: Land with of the screw	(cm)
h	: Hight of the flight	(cm)
K	: Quantity defined by Eq. (5)	(−)
L	: Length of the screw	(cm)
N	: Rotational speed of the screw	(rpm)
P_1, P_2	: Pressure of powder at inlet and outlet	(kg/cm^2)
Q	: Conveying rate in weight or in volume	(kg/min) or (cm^3/min)
γ	: Bulk density of the powder	(kg/cm^3)
θ	: Angle of direction of solid movement	(°)
μ_B	: Coefficient of friction between solids and conveyor barrel	(−)
μ_s	: Coefficient of friction between solids and root of the screw	(−)
φ	: Hold-up ratio defined by Eq. (2)	(−)
ϕ_a	: Helix angle of the screw	(°)
ϕ_B	: Average helix angle at the screw periphery	(°)
ϕ_s	: Helix angle at the root of the screw	(°)

LITERATURE CITED

1) Sakamoto, I. : Graduation thesis, Colledge of Engineering, University of Osaka Prefecture (1963)

2) Kutsukake, M. and M. Nishizawa : Garaduation thesis, The Faculty of Textile Science and Technology, Shinshu University (1967)
3) Majima, U. : *Zoku shin kagaku-kogaku koza*, No. 18, "Conveyor", Nikkan kogyo shin-bun-sha (1960)
The Soc. of Chem. Engrs., Japan ed. : *Kagaku-kogaku ben-ran* (1968)
4) Uematsu, T. : *Kagaku kikai gijitsu*, No. 5, 187 (1953)
5) Sanoh, Y., S. Nakano and T. Yano : *Funsai*, No. 6, 8 (1961)
6) Darnell, W. H. and E. A. J. Mol: SPE Journal, 12, Apr., 20 (1956)
7) Matsumoto, K., S. Yoshikawa and M. Nakamura: Chem. Eng. (Japan) 23, 385 (1959)
8) Arai, C., M. Hayakawa and Y. Sanoh: Paper presented at 1st autumn meeting of The Soc. of Chem. Engrs, Japan, p. 141 (1967)