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A Study of the Horizontal and Inclined Continuous-Flow Conveyors*

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The authors studied experimentally the characteristics of the horizontal and inclined continuous-flow conveyors. The experiments show that : (1) the volumetric efficiency and the chain tension are independent of the chain velocity ; (2) there is an optimum ratio of the depth of trough to the pitch of flight ; (3) the optimum ratio is given by the inclination of trough ; and (4) the clearance between the wall of trough and the edge of flight must be made about three times as large as the mean diameter of materials.

Then the authors obtained the formula to calculate the chain tension. The calculated values of the chain tension are in good agreement with the experimental ones. From the results of the experiments and calculations, it has been cleared that the power of inclined conveyors is given by the sum of the power of horizontal conveyors and that of lifting materials.

1. Introduction

The continuous-flow conveyors are used to transport the pulverized and granular materials. Several works on the continuous-flow conveyors were previously made by Noguchi, Yamauchi and Tsumaki⁽¹⁾⁽²⁾. They studied theoretically the basic relation between the characteristics of materials and the size of conveyors.

Nowadays the continuous-flow conveyors are designed by using the charts⁽³⁾ which have been invented by experience.

In this experiment, in which sand and coal are conveyed, the volumetric efficiency and the chain tension are measured. And then from the equilibrium of the forces acting on materials in the trough, the formula to calculate the chain tension is obtained. The calculated values are in good agreement with the experimental results.

2. Nomenclature

a_1 : sectional size of flight
 b : width of trough
 b_1 : width of flight
 d : size of materials
 G : weight of discharge per unit time
 h_m : mean height of materials in the trough
 L : distance from the feeding to the discharge

port

Q : weight of materials in the trough
 T : tension required for conveying materials
 T_0 : no-load tension
 T_t : total tension
 t : pitch of flight
 v : mean velocity of materials
 v_c : chain velocity
 v_0 : velocity of materials without wall effect
 w : weight of chain per unit length
 α : angle of inclination
 γ : apparent specific weight of material
 δ : clearance between the edge of flight and the wall of trough
 η : conveyor efficiency
 η_t : total efficiency
 η_v : volumetric efficiency
 η_{v0} : volumetric efficiency without wall effect
 μ_c : coefficient of friction between the chain and the trough
 μ_i : coefficient of internal friction
 μ_s : coefficient of friction between the wall of trough and materials
 ϕ_i : angle of internal friction
 $\phi_b = h_m/b$
 $\phi_t = h_m/t$

3. Apparatus and procedure

3.1 Apparatus and materials

The arrangements of the apparatus used in this paper are shown in Fig.1. The materials stored in the hopper are fed into the trough at a uniform rate

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through the orifice fitted in the hopper, and are conveyed to the discharge port by the chain shown in Fig. 2. To change the discharge, seventeen orifice plates, having a circular hole of 10 to 43 mm in diameter, are used. The flight of the conveyor-chain is made of mild steel wire with a square section of size $a_1=3.2$ mm, as shown in Fig. 2. The authors use two conveyor-chains, and the pitch of flight t is 25.4 mm and 50.8 mm, i.e. $t/a_1=7.94$ and 15.9.

The inclination of trough α and the distance from the feeding to the discharge port L are listed in Table 1. The case of $\alpha=0$ is called horizontal conveying, and others inclined conveying.

For easy replacing, the trough is fixed with bolts and nuts. In the case of horizontal conveying the troughs 1, 2 and 3 are used, the dimensions of which are shown in Table 2. In the case of inclined conveying, only the trough 2 is used.

The chain velocity v_c can be changed by replacing a spur gear a (Fig. 1) with different ones, in this paper v_c is selected as follows :

$v_c=0.1, 0.2, 0.3, 0.4$ and 0.5 m/sec.

To obtain the values of chain tension, a pick-up using the strain gauge is mounted on the axis of the chain wheel a and the strain proportional to the tension is recorded by a pen writing oscillograph.

Three kinds of materials are used in this experiment, and their characteristics are shown in Table 3.

Both sand B and coal are granular materials of the same size and about four times as large as sand A in diameter. The apparent specific weight of coal used in horizontal conveying is $\gamma=835$ kg/m³ and that in inclined conveying is $\gamma=804$ kg/m³.

The values of the coefficients of friction μ_i and μ_s shown in Table 3 are given by a shearing test⁽⁴⁾.

In this paper the authors obtain the volumetric efficiency and the chain tension by changing the discharge of materials, the pitch of flight and the chain velocity.

3.2 Volumetric efficiency

The ratio of the mean velocity of materials v to the chain velocity v_c is denoted by η_v , i.e.

$$\eta_v = v/v_c \dots\dots\dots (1)$$

In order to measure the weight of all the materials in the trough Q in a steady state of conveying, the feed is stopped and instantaneously a vessel is placed at the discharge port. If materials are moved with the same velocity as the chain, the discharge is equal to Qv_c/L . The ratio of the actual discharge G to Qv_c/L , therefore, represents the volumetric efficiency, and also the weight Q is shown by

$$Q = GL/v,$$

so that the ratio is transformed as follows ;

$$\frac{G}{Qv_c/L} = \frac{G}{(GL/v)v_c/L} = \frac{v}{v_c} = \eta_v \dots\dots\dots (2)$$

Therefore η_v defined by Eq. (1) is the volumetric efficiency. Neglecting the effect of the wall, it is considered that the mean velocity of materials v is the velocity at any point between E and F shown in Fig. 3. In the trough 3 which is fairly wider than the others, materials near the wall move little. In this paper the authors assumed that the velocity distribution of materials is

Fig. 1 Apparatus

Fig. 2 Conveyor-chain and section of trough

Table 1 Inclination of trough α and distance from the feeding to the discharge port L

α°	L m
-10.6	1.89
0	1.91
9.5	1.81
20.0	1.81

Table 2 Dimensions of trough

	a mm	b mm	b_1/b
Trough 1	40	49.4	0.91
Trough 2	45	55.6	0.81
Trough 3	45	64.5	0.70

represented by ACDB in Fig. 3, and that the velocity v_0 which is considered a constant between C and D, is not affected by the wall. When there is no frictional force between the materials and the wall, materials near the wall move with the velocity v_0 . In this case the volumetric efficiency is given by

$$\eta_{v0} = v_0/v_c \dots\dots\dots (3)$$

then η_{v0} is called the volumetric efficiency without wall effect. Since the discharge must be equal in two cases of velocity distributions, AEFB and ACDB, the relation between v_0 and v is given as

$$v_0(b+b_1+d)/2 = vb,$$

then

$$\eta_{v0} = 2\eta_v / \{1 + (b_1/b) + (d/b)\} \dots\dots\dots (4)$$

where it is considered that the length CD is equal to the sum of the width of flight b_1 and the size of materials d .

Let ψ_t be the ratio of the mean height of materials in the trough h_m to the pitch of flight t , i. e.

$$\psi_t = h_m/t \dots\dots\dots (5)$$

then the measured values of the volumetric efficiency are plotted against the values of ψ_t . Neglecting the volume of the chain and the flight, the mean height h_m is represented by

$$h_m = Q/(\gamma b L) \dots\dots\dots (6)$$

3.3 Chain tension

The chain tension T required for conveying materials is obtained as the difference between two tensions, T_0 and T_t . T_0 is the no-load tension and T_t is the total tension for conveying materials, i. e.

$$T = T_t - T_0 \dots\dots\dots (7)$$

The values of the tension T can be calculated

Table 3 Materials used in the experiment

	Sand A	Sand B	Coal
Size mm	0.3~0.6	1.2~2.5	1.2~2.5
Apparent specific weight γ kg/m ³	1 320	1 410	835, 804
Coefficient of internal friction μ_i	0.57	0.62	0.57
Coefficient of friction between wall and materials μ_s	0.49	0.50	0.40

Fig. 3 Velocity distribution of materials in the trough

by the equation from the equilibrium of the forces acting on materials. It is considered that four kinds of forces act on the element of materials bounded by ABCD in Fig. 4, namely, the total pressure of materials on the faces BA and CD, the gravitational force on the element, the force between the wall of trough and materials, and the force from the flight. If the pressure on the faces BA and CD is given by the product of the apparent specific weight γ and the depth from the upper surface of materials, and if the direction of pressure is normal to the faces, then the resultant of the pressure is zero since the total pressures on BA and CD are equal and opposite.

With the notation shown in Fig. 4, the weight of the element dQ is represented by

$$dQ = \gamma b h_m dL.$$

The force from the side wall is composed of the pressure normal to the wall and the frictional force having the opposite direction to that of conveying. If the pressure on the wall is distributed in the same way as on the face BA, the frictional force on one side dF_s is given by

$$dF_s = (1/2) \mu_s \gamma h_m^2 \sec \alpha dL.$$

Observing the motion of materials in the trough, it is seen that the materials are conveyed on the thin layer of the materials staying on the bottom of trough. Then the force acting on the bottom AD, dF_b , makes an angle ϕ_i with the normal to AD, where ϕ_i is the angle of internal friction and is equal to $\tan^{-1} \mu_i$.

The force from the flight dT must be equal and opposite to the sum of the forces mentioned above, so that dT is given by the sum of $2dF_s$ and dT_1 which is the component of dF_b . Then

$$dT = \sin(\phi_i + \alpha) \sec \phi_i dQ + \mu_s \gamma h_m^2 \sec \alpha dL.$$

Therefore the tension required for conveying materials T is

$$T = \int_{L=0}^L dT = \psi_b \gamma b^2 L \{ \sin(\phi_i + \alpha) \sec \phi_i + \mu_s \psi_b \sec \alpha \} \dots\dots\dots (8)$$

where ψ_b is given by

$$\psi_b = h_m/b \dots\dots\dots (9)$$

Fig. 4 Forces acting on materials in the trough

From Eq. (8) the dimensionless number of the tension is expressed by

$$T/(\gamma b^2 L \cos \alpha) = \psi_b \tan \alpha + \mu_s \psi_b^2 \tan^2 \alpha + \mu_i \psi_b \{1 + (\mu_s/\mu_i) \psi_b\} \quad (10)$$

In the case of $\alpha=0$, only the third term of Eq. (10) remains, then the first and the second terms represent the effect of the inclination. The first term of Eq. (10) is a dimensionless value of the tension to lift materials.

In this paper the relation between the values of $T/(\gamma b^2 L \cos \alpha)$ and ψ_b is treated.

3.4 Total efficiency and conveyor efficiency

When the materials of unit weight are pushed up along a plane making an angle α with the horizontal plane, the force equal to $\sin(\phi+\alpha)/\cos \phi$ is required, where ϕ is the angle of friction between materials and the plane. When the materials, of which weight is G per unit time, are conveyed over a distance L on the plane, the power

$$GL(\tan \phi \cos \alpha + \sin \alpha)$$

is required. Then the total efficiency η_t can be defined by

$$\eta_t = GL(\mu_i \cos \alpha + \sin \alpha)/T_i v_c \quad (11)$$

where $T_i v_c$ is the power given to the conveyor. From Eqs. (2) and (7), Eq. (11) becomes

$$\eta_t = \eta_v \{Q(\mu_i \cos \alpha + \sin \alpha)/T\} \{1 - (T_0/T_i)\} \quad (12)$$

Let

$$\eta = Q(\mu_i \cos \alpha + \sin \alpha)/T \quad (13)$$

then η is the ratio of the force needed for pushing up all the materials to the force actually acting on materials, so it is called the conveyor efficiency.

4. Experimental results

4.1 Volumetric efficiency

To investigate the effect of the chain velocity v_c and the pitch t on the volumetric efficiency η_{v0} given by Eq. (4), the experimental results of horizon-

Fig. 5 Relation between η_{v0} and ψ_t

tal conveying of sand A with the trough 2 are plotted in Fig. 5. In the evaluation of η_{v0} expressed by Eq. (4), the mean value of the maximum and minimum size of materials is used for d . From Fig. 5 it is clear that the relation between η_{v0} and ψ_t is independent of v_c and t . The results shown in Fig. 6 are those of a case using sand A and three kinds of troughs. In the figure η_{v0} is a little smaller in the trough 3 than the other, because the clearance δ between the edge of flight and the wall of trough is too wide to convey materials near the wall. The results of horizontal conveying with coal in Fig. 7 show that η_{v0} is independent of the value of δ . As $b_1 = b - 2\delta$ with the notation in Fig. 3, Eq. (4) becomes

$$\eta_v = \{1 - (\delta/b) + (d/2b)\} \eta_{v0}.$$

Therefore η_v becomes larger with the decrease of δ , and so it is preferable to use a trough with small δ .

To investigate the effect of the inclination on the efficiency η_{v0} , the experimental results for the various values of angle α shown in Table 1 are plotted in Fig. 8. The value of η_{v0} is smaller for a

Fig. 6 Relation between η_{v0} and ψ_t

Fig. 7 Relation between η_{v0} and ψ_t

steeper inclination.

Figs. 5 to 8 show that the value of η_{v0} increases with ψ_t and becomes constant when ψ_t is larger than ψ_{tc} . The value of ψ_{tc} , which depends on the kinds of materials and the inclination of trough, is given by Fig. 8, and plotted in Fig. 9 against the

(a) Sand A

(b) Sand B

(c) Coal

Fig. 8 Relation between η_{v0} and ψ_t

angle α . The relation between ψ_{tc} and α is represented by the full line for sand A and by the broken line for sand B and coal. It is considered that the difference between these two lines is due to the size of materials, so that the relation given by the full line is used for the practical device because the ratio of the size of materials to the dimension of the practical device is larger than the ratio for the experimental device.

4.2 Chain tension

The relation between the dimensionless number of the tension $T/(\gamma b^2 L \cos \alpha)$ and ψ_b is given by Eq. (10). The experimental results of the dimensionless number are plotted against ψ_b in Figs. 10 to 12. The values calculated by Eq. (10) are also plotted

Fig. 9 Relation between ψ_{tc} and α

Fig. 10 Relation between $T/(\gamma b^2 L)$ and ψ_b

Fig. 11 Relation between $T/(\gamma b^2 L)$ and ψ_b

by the full lines.

From Fig. 10 for horizontal conveying with sand A, it is considered that the dimensionless number $T/(\gamma b^2 L)$ is independent of the width of trough, the chain velocity and the pitch of flight. In Fig. 11 showing the results with coal the values of $T/(\gamma b^2 L)$ for the trough 1 ($b_1/b=0.91$) are larger than those for the others. In this case the mean value of clearance δ is 2.2 mm and the maximum size of coal is 2.5 mm. So the tension increases for clogging and crushing of materials between the edge of flight and the wall of trough.

(a) Sand A

(b) Sand B

(c) Coal

Fig. 12 Relation between $T/(\gamma b^2 L \cos \alpha)$ and ϕ_b

From these results for the tension and the volumetric efficiency, it is seen that the optimum relation between the clearance δ and the mean size of materials d is given by

$$\delta \approx 3d \quad (14)$$

Fig. 12 shows the results with three kinds of materials for changing the angle of inclination. The relations represented by Eq. (10) are plotted by the full line in the figure, and are in good agreement with the experimental results. If the inclination of trough is not steeper than 20° , which is the maximum value in this experiment, the second term in the right side of Eq. (10) is smaller compared with the first. Then the effect of the inclination on the tension is represented by the first term of Eq. (10) which is a dimensionless value of the tension for lifting materials.

From these experiments and calculations it is considered that the dimensionless number $T/(\gamma b^2 L \cos \alpha)$ is a function of ϕ_b , the angle α and the coefficients of friction μ_i and μ_s , and it is independent of the chain velocity, the pitch of flight and the width of trough.

Let w be the weight of the conveyer-chain per unit length, L its length and μ_c the coefficient of friction between the chain and its sliding face, then the no-load tension T_0 is given by

$$T_0 = \mu_c w L_c \quad (15)$$

and using the length L ,

$$L_c \approx 2L,$$

so from the above equation the coefficient μ_c is given by

$$\mu_c = T_0 / (2wL) \quad (16)$$

The values of μ_c obtained from T_0 are shown in Table 4 together with the coefficients of friction μ_i and μ_s . From the results of Table 4, it is seen that the values of μ_c are approximately equal to those of μ_s , therefore it is easy to calculate the total chain tension with Eqs. (10) and (15). As Eq. (15) for T_0 contains w which is a function of the pitch t , and the total tension T_t is equal to $(T + T_0)$, then the total tension is also a function of the pitch t .

Table 4 Coefficients of friction

	t mm	μ_c	μ_i	μ_s
Sand A	25.4	0.52	0.57	0.49
	50.8	0.51		
Sand B	25.4	0.49	0.62	0.50
	50.8	0.47		
Coal	25.4	0.42	0.57	0.40
	50.8	0.40		

Pitch of flight $t=25.4$ mm : Weight of chain $w=0.74$ kg/m

Pitch of flight $t=50.8$ mm : Weight of chain $w=0.54$ kg/m

4.3 Total efficiency

The total efficiency η_t is given by a product of three quantities η_v , η and $\{1 - (T_0/T_t)\}$ as seen in Eq. (12).

To investigate the effect of the pitch on η_t , the results of horizontal conveying with sand A are shown in Fig. 13. For the larger value of ψ_b , the longer the pitch is, the higher the total efficiency η_t becomes, because η_v is constant for the larger value of ψ_b corresponding to ψ_{tc} , and the value of $\{1 - (T_0/T_t)\}$ is larger for a longer pitch in view of Eq. (15) and the value of w shown in Table 4.

Since the volumetric efficiency becomes lower for too larger pitch, the value of the pitch should be so selected as to correspond to ψ_{tc} shown in Fig. 9. As ψ_{tc} is larger for a steeper inclination, the chain used for a larger angle of inclination must be small in pitch.

5. Conclusion

The relation between the volumetric efficiency without wall effect η_{v0} and ψ_t expressed by Eq. (5) is independent of the chain velocity, the pitch of flight and the width of trough, and varies with the kinds of materials and the inclination of trough. The efficiency η_{v0} becomes constant for values of ψ_t larger than ψ_{tc} shown in Fig. 9.

In order to get the maximum efficiency, the pitch should be obtained from the value of ψ_{tc} .

The clearance between the edge of flight and the wall of trough is decided by Eq. (14).

The tension required for conveying materials is expressed by Eq. (10), and is also independent of

Fig. 13 Relation between η_t and ψ_b

the chain velocity and the pitch. In the case of inclined conveying, only the amount of lifting materials increases in the chain tension compared with horizontal conveying.

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References

- (1) N. Noguchi, K. Yamauchi and M. Tsumaki: *Preprint of the 31st Annual Meeting of Japan Soc. Mech. Engrs.*, (April, 1954), No. 244.
- (2) N. Noguchi, K. Yamauchi and M. Tsumaki: *Preprint of the 32nd Annual Meeting of Japan Soc. Mech. Engrs.*, (April, 1955), No. 529.
- (3) W.G. Hudson: *Conveyors and Related Equipment*, (1954), p. 127, John Wiley and Sons.
- (4) D.P. Krynine: *Soil Mechanics*, (1941), p. 178, McGraw-Hill.