621.86.067:539.215

Paper No. 164-12

Feed Rate of a Rotary Feeder*

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The revolution characteristic of feed rate of a rotary feeder is examined theoretically and experimentally when back pressure is not applied to the feeder outlet. The revolution giving the maximum feed rate is dependent on the inlet dimension, the total volume of wheel rooms and the number of wheel rooms of the feeder and on the relaxation time of solid particle. For solids having large relaxation time the maximum feed rate becomes independent of the relaxation time. Discrepancy between experimental results and a theory is largely due to irregular outflow of solids from a hopper to the feeder inlets.

1. Introduction

The rotary feeder, which is one of solids feeders, has a similar structure to a revolving door and its rotating shaft is situated horizontally. The solid particles are charged into the wheel rooms at the upper part of the feeder under the gravity and then discharged at the lower part of the feeder after half a rotation. Since the feed rate can be changed by the revolving speed of the wheel, the rotary feeder is widely used as a handy solids feeder of which feed rate is adjustable. Moreover, since the existence of the wheel room keeps, to a certain degree, air tight between the inlet and the outlet of the feeder, the solid particles can be fed into a highly pressurized region. Then, for a pneumatic transport system the rotary feeder is used as a feeder of solid particles into the conveying pipe.

Variation of the feed rate with revolving speed is called the revolution characteristic of the feeder. This characteristic depends not only on the structure of the feeder and the physical properties of solid particles but also on higher pressure at the feeder outlet, which is called back pressure, in case of the feeding to a pressurized region. In some cases the back pressure gives rise to a feed stoppage.⁽¹⁾

The solid particles are usually supposed to fall into the feeder from a hopper under the gravity. But the outflow from the hopper generally depends on the hopper geometry and it is not always smooth. Sometimes, presumably because of a bridging phenomenon near the hopper outlet, the outflow pulsates to cause a variation in the feed rate. Therefore, the feed rate of the rotary feeder also varies with the operating condition. Another important problems in the rotary feeder is one of leakage air characteristic, which is closely related to air tightness when the back pressure is applied. References on these problems of the rotary feeder are, however,

relatively few.⁽²⁾⁽³⁾ The present paper describes the revolution characteristics of the feed rate when the back pressure is not applied, as one of fundamental characteristics.

The control of the feed rate is based on a change of volume of solid particles in the wheel rooms according to the speed. When the speed is low enough, the solid particles completely fill up the room during their passing the feeder inlet and then are discharged from the outlet. Then, in this case, the feed rate increases in proportion to the speed, since interception of the flow of solid particles decreases with an increasing speed. When the speed attains a value at which the solids completely fill up the room just within their passing time at the inlet, the interception of the flow by the wheel room disappears and the feed rate takes a maximum. When the speed increases further, the solid particles cease to completely fill up the wheel room within the passing time and then, the feed rate decreases in inverse proportion to the speed. Now we consider the situation at the feeder outlet. Since the solid particles obtain an angular velocity by the rotation, they do not always fall vertically at the outlet. Then, some particles remain in the wheel rooms without being discharged and they cause a cutdown of the feed rate. This influence significantly appears in higher speed range in which the solid particles completely fill up the wheel room at the feeder inlet.⁽³⁾ It is, however, important that the revolution characteristic be examined at the feeder inlet, since the control of the feed rate primarily depends on the condition of solids inflow to the feeder. From this point of view we investigate a case where the solid particles fill the wheel room under the free falling due to the gravity alone and show that the speed at which the feed rate takes a maximum is determined by geometry of the feeder alone.⁽⁴⁾ It is shown, however, that for solids having small free falling velocity, agreement between this theory and measurements is not satisfactory and that physical material properties of the solid particles also influence considerably. Therefore, in the present paper, we examine the revolution characteristic of the feed rate including the physical properties of solid particles by taking account of the fluid drag on the particles.

* Received 4th October, 1976.

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2. Theory

It is assumed that the solid particles smoothly flow into the feeder inlet and that the back pressure is not applied. In the first place we consider the case when the number of revolutions per minute n is smaller than $(n)_{\max}$ at which the feed rate takes a maximum. In this case the solid particles completely fill the wheel room as above-mentioned, and the solids feed rate per minute G is in proportion to n and is given by

$$G = \gamma_b V_0 n, \quad n \leq (n)_{\max} \quad (1)$$

where γ_b is the bulk specific weight of the solid particles, V_0 is the total volume of the wheel rooms.

Next we consider the case when $n \geq (n)_{\max}$. In this case it is unlikely that the solid particles completely fill the wheel room. Then it is necessary to consider the situation of solids filling the wheel room. We consider the revolution characteristic of the feed rate of the rotary feeder by replacing the revolving motion of the wheel room with a horizontally rectilinear motion of a series of vessels having the same velocity as the revolving speed, as shown in Fig.1. The revolution characteristic of the feed rate is obtained if we can calculate the volume of solid particles which fall from the feeder inlet into the vessel as they pass the inlet. For this purpose it is useful to consider the solid particles as a fluid mass. A problem of how much of a fluid can flow into the vessel is equivalent to one of how far the leading boundary surface of the fluid can advance. In order to examine such movement of the bounding surface of fluid, it is useful to apply the Lagrangian aspects which follow the motion of individual fluid particles.

The equation of motion for a single solid particle in still air is given by

$$\frac{\pi d^3}{6} \gamma_p \frac{d^2 y}{dt^2} = \frac{\pi d^3}{6} \gamma_a - c_D \frac{1}{2} \gamma_a \left(\frac{dy}{dt} \right)^2 \quad (2)$$

where d is the particle diameter, γ_p is the material specific weight of the solid particles, γ_a is the specific weight of air, g is the gravity acceleration, c_D is the drag coefficient of a single solid particle in the particles cloud, y is the vertically downward co-ordinate of the particle from the feeder inlet and t is the time.

In ordinary fluid such as air, forces

Fig.1 Feed model of rotary feeder

due to the viscous stresses or the Reynolds stresses work which appear as a result of interaction between the molecules or the fluid particles. But in this case the solid particles fall through the still air under the gravity and transversal motion of the particles is assumed as not appreciable, thus the interaction forces between particles are neglected. Nondimensionalizing Eq.(2) by d and g , we have

$$\frac{d^2 y'}{dt'^2} = 1 - \frac{3}{4} c_D \frac{\gamma_a}{\gamma_p} \left(\frac{dy'}{dt'} \right)^2 \quad (3)$$

where the prime denotes the nondimensional quantities. If we use the drag coefficient of a single sphere in the infinite fluid, c_D will be a function of the Reynolds number and this function will be variable with the particle velocity even following Stokes' law and Newton's law. However, by Newton's law the factor to the second term of the right hand side of Eq.(3) is an order of 10^{-4} when $\gamma_a/\gamma_p \approx 10^{-3}$, and in this case the air drag is negligible compared with the gravity force. For the same Reynolds number, c_D from Stokes' law is smaller than that from Newton's law, and in the above-mentioned sense for a whole range of (dy'/dt') we can estimate c_D from Stokes' law; namely $c_D = 24\nu/(dy/dt)d$, where ν is the kinematic viscosity of air. Using this, Eq.(2) is solved for initial conditions $y = dy/dt = 0$ at $t = 0$, yielding:

$$y(t) = gt_* [t - t_* (1 - \exp(-t/t_*))] \quad (4)$$

where t_* is the relaxation time of the particle according to Stokes' law which is calculated as

$$t_* = \frac{1}{18} \frac{\gamma_p}{\gamma_a} \frac{d^2}{\nu} \quad (5)$$

Since the volume of the solid particles

Fig.2 Filling manner of solid particles

filling the wheel room is equal to their volume falling from the feeder inlet, we calculate the latter. Figure 2 schematically illustrates a manner of falling of the particles from the feeder inlet into the wheel room. When the longitudinal length of the wheel room is H , the rotational velocity is u , then H/u is the time interval for one wheel room to pass the feeder inlet. Within this time the solid particle which starts from the feeder inlet goes into the wheel room by a distance of $y(H/u)$. Consequently, the weight of solid particles which fall through the small segment Δl in the longitudinal direction within the time H/u is $\gamma y(H/u)b\Delta l$, provided that the solid particles fall continuously with the bulk specific weight and that b is the axial length of the feeder inlet. Then, the total weight w falling from the feeder inlet is given by

$$w = \gamma b l g t_* \left[\frac{H}{u} - t_* \left\{ 1 - \exp \left(-\frac{H}{ut_*} \right) \right\} \right]$$

where l is the circumferential length of the feeder inlet.

When the number of wheel rooms is z , and their inlet radius is R , then

$$H = 2\pi R_z / Z, \quad u = \pi n R_z / 30$$

and we have $H/u = 60/Zn$. Therefore the feed rate G is wZn and is given by

$$G = Z b l g \gamma t_* \left[\frac{60}{Z} - n t_* \left\{ 1 - \exp \left(-\frac{60}{Z n t_*} \right) \right\} \right] \quad [n \geq (n)_{\max}] \quad (6)$$

When $60/Znt_*$ becomes large G tends to $1800 b l g \gamma t_* / Zn$, which agrees with the case when the air drag is neglected.⁽⁴⁾ It is seen from Eq.(6) that the feed rate characteristic for a given feeder of different solids is correlated by the diagram of $G/\gamma t_*$ versus nt_* . Nondimensionalizing Eq.(6), we obtain

$$\frac{G}{Z b l g \gamma t_*^2 n} = \frac{60}{Z n t_*} - \left\{ 1 - \exp \left(-\frac{60}{Z n t_*} \right) \right\} \quad [n \geq (n)_{\max}] \quad (7)$$

It follows therefrom that the feed rate characteristics for all kinds of the solid particles in all rotary feeders of same shape can be correlated by Eq.(7). And for $n \leq (n)_{\max}$, the nondimensional feed rate is given by Eq.(1)

$$\frac{G}{Z b l g \gamma t_*^2 n} = \frac{V_0}{Z b l g t_*^2} \quad [n \leq (n)_{\max}] \quad (8)$$

Another quantity which indicates the feed rate characteristic is the filling rate or the volume efficiency η_v defined by $G/\gamma_s V_0 n$. For $n \leq (n)_{\max}$, η_v is unity and for $n \geq (n)_{\max}$, it is calculated by Eq.(6) as

$$\eta_v = \left(\frac{Z b l g t_*^2}{V_0} \right) \left[\frac{60}{Z n t_*} - \left\{ 1 - \exp \left(-\frac{60}{Z n t_*} \right) \right\} \right] \quad [n \geq (n)_{\max}] \quad (9)$$

As mentioned in the section 1, $(n)_{\max}$ is the maximum number of revolutions in the case of $\eta_v = 1$. Then it is given by Eqs.(9) and (6), or it is n which gives $\eta_v = 1$ in Eq.(9). The value depends on the feeder structure and on the kinds of solid particles. For a given feeder the larger the value of t_* , the larger $(n)_{\max}$ is, and for $t_* \rightarrow \infty$ which corresponds to the case of neglecting the air drag, $(n)_{\max}$ tends to $(1800 b l g / Z V_0)^{1/2}$ and then G tends to $\gamma_s (1800 b l g V_0 / Z)^{1/2}$.⁽⁴⁾ When $n \leq (n)_{\max}$, since G is in proportion to n , the control of the feed rate is easy. Therefore the feeder having a larger $(n)_{\max}$ is more useful. For given solid particles, the feeder which has a larger inlet area and smaller Z and V_0 is desirable. However, it is not preferable for Z to be too small, when the requirement of air tightness is severe.

3. Experiment

3.1 Experimental apparatus and procedure

Fig.3 Schematic diagram of experimental apparatus

Fig.4 Revolutions giving the maximum feed rate versus relaxation time of solid particle

Table 1 Physical properties of tested solids

Properties	d	γ_p	γ_b	t_*
Solids	mm	kg/m ³	kg/m ³	s
Glass beads	1	2520	1520	6.4
	44×10^{-3}	2520	1340	0.0126
Pellets	3.2	921	585	0.66
Rape seeds	1	1060	621	0.603
Alumina	30×10^{-3}	3900	920	0.0091
P.V.C. powder	50×10^{-3}	1330	524	0.0088
Rice bran	10×10^{-3}	1320	320	0.0004

(a) $n=75$ rpm (b) $n=150$ rpm

Fig.5 Photographs showing how the pellets fall in the feeder

Fig.6 Photographs showing how the glass beads ($44 \mu\text{m}$) fall in the feeder ($n=75$ rpm).

Figure 3 shows the experimental apparatus. The tested rotary feeder has the following specification; $V_0=1.6$ l/rev, $l=82$ mm, $R_0=75$ mm, $b=150$ mm, $Z=8$ and the clearance of 15/100. By the speed reducer n is changed. The feed rate G is obtained by the use of load cell. The diameter of the hopper outlet is 105.3 mm. A cyclone separator and an injection feeder are used to return the solids to the hopper. Table 1 gives the physical properties of the tested solid particles, where t_* for the pellets is obtained from the measured value of the free falling velocity and the others are calculated by Eq.(5).

Finally, in order to observe the solids flow pattern in the feeder, a rotary feeder of approximately same size as the tested feeder in cantilever type is constructed and one of side walls of the wheel is a transparent plastic plate. The solids flow pattern in the feeder is photographed through the transparent plate using an electronic flash synchronized to the revolutions of the feeder.

3.2 Experimental results and discussion The calculated values of $(n)_{\max}$ for the tested feeder are plotted against t_* in Fig.4. For the solids having t_* larger than 1 sec, the value is nearly equal to that in the case of neglecting the air drag. When t_* is very small such as rice bran, $(n)_{\max}$ is small and it is thought that the feed by the rotary feeder becomes difficult, which was experimentally confirmed.

Figure 5 shows a flow pattern of pellets in the feeder. When $n=75$ rpm, as shown in Fig.5 (a), the pellets almost fill up the wheel room and it is seen that the leading boundary surface is approximately parabolic as shown by Eq.(4) for larger t_* . Figure 5 (b) shows the case of $n=150$ rpm, which is larger than $(n)_{\max}$. It is noted that, as shown in both Figs.5 (a) and (b), there remain some particles which are not discharged from the wheel rooms. Figure 6 shows the case for $44 \mu\text{m}$ glass beads at $n=75$ rpm, which is larger than $(n)_{\max}$. As seen from this figure, the filling of the feeder with solids is random and sometimes there is no filling. Because of this the measured values of G are scattered, although the discharge at the feeder outlet is relatively smooth. Thus, in the case that the filling of the feeder is not smooth, the

deviation of measurements from the theory will be wide. This irregularity of the filling is presumably due to a bridging phenomenon near the hopper outlet and then the discharge of solids from the hopper becomes random.

Figure 7 shows the relation of G to n for different solids. It is seen that for each solid $(n)_{\max}$ is roughly predictable from the present theory. It is also seen that for solids having comparatively large d and t_* , the measured feed rate near $(n)_{\max}$ is lower than that by the present theory. It seems partly true that the solid particles cannot be completely discharged at the feeder outlet and some particles remain in the wheel rooms. On the other hand, for solids having small t_* the feed rate at larger n is less than that from the present theory, which is likely caused by the fact that the falling of solids into the wheel room is disturbed by an air flow generated near the inlet by high speed rotation of the wheel. Moreover, in this apparatus, the hopper is connected to the feeder by the flange, and the vibration of the feeder acts on the hopper, which may in turn influence the feed rate.

As for the G - n relation in the glass beads, for the $44\mu\text{m}$ beads the scatter of measured values as well as disagreement with the present theory are significant. On the other hand for 1mm beads, when $n > (n)_{\max}$, G is larger than that from the present theory. The glass beads of 1mm have much higher fluidity. If it is assumed that the particle has an initial velocity v_0 at $y=0$, G is given by

$$G = Z b l g r b n t_*^2 \left[\frac{60}{Z n t_*} - \left(1 - \frac{v_0}{g t_*} \right) \left\{ 1 - \exp \left(- \frac{60}{Z n t_*} \right) \right\} \right] \quad (10)$$

The dotted line in Fig. 7 is drawn for v_0 which makes the measured value equal to the value by Eq. (10) at one point of the line of $n > (n)_{\max}$; $v_0 = 0.0545 \text{ m/s}$, whose value corresponds to the velocity that the solid would attain at $y = 0.15 \text{ mm}$ with zero initial velocity when falling under the gravity alone. It is noted that the clearance of the tested feeder is 0.15 mm .

Figure 8 shows the relation of the non-dimensional feed rate defined by the left hand side of Eqs. (7) and (8) to nt_* . The curve declining toward the right indicates Eq. (7) and the straight lines parallel to the abscissa show Eq. (8). When nt_* is larger, the slope of Eq. (7) tends to be proportional to $(nt_*)^{-2}$. Although shown as a double logarithmic plot, the feed rate characteristics for different solids can be practically explained by the present theory.

4. Conclusions

The revolution characteristics of the feed rate of the rotary feeder are examined when the back pressure is not applied. The experimental measurements are on the whole explained by the present theory. The rotary feeder is usually used under the feed hopper, and in this case for the solid particles which tend to give rise to a bridging phenomenon, agreement with the present theory is not good. The range of the rotary feeder to control the feed rate becomes wider for solids having

Fig. 7 Feed rate versus revolutions

Fig. 8 Nondimensional feed rate characteristics

larger relaxation time and for given solid particles it becomes wider both for larger feeder inlet area and smaller total volume of the wheel rooms as well as larger number of wheel rooms.

Finally the authors wish to thank Messrs. N. Nagasoe, K. Moriwaki, S. Dateki, M. Morihata, H. Iwasaki and S. Kaku for their co-operation which has contributed to the present work.

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