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A Study of Airlift for the Feeder of Solids*

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Some experimental and theoretical studies of airlift, which is used for a feeder of particles in the pneumatic conveyance system are described.

The feeding performances are obtained experimentally using several kinds of particles, and pressure losses in airlift are analysed to estimate the power required; which are compared with experimental ones. The drag coefficients of particles in a fully developed turbulent pipe flow are determined experimentally to make an accurate calculation of the pressure losses.

The feeding performance of airlift can be represented by formulae using the results of a simple discharge test of particles from a two-dimensional port. The agreement of the calculated pressure losses with experimental ones is quite good when the calculation is made using the drag coefficient of particles obtained in the test.

1. Introduction

A pipeline system for a pneumatic conveyance is in need of feeders to supply the materials from a storage tank to the pipeline. The feeder of particles can be classified in two groups; feeders using mechanical forces such as a rotary feeder or an electromagnetic feeder and ones using fluid forces such as a blow-tank(1) or an ejector feeder. Airlift is a kind of blow-tank but the pressure required is far smaller than that for the blow-tank and is suitable as the feeder of particles with relatively good fluidity.

In the present paper, the feeding performances and power required for airlift are discussed.

The feeding performance are examined by the tests using several kinds of particles and pipes with different diameters, and the mechanism of discharge from airlift is discussed. The formulae representing the feeding performances using the results of a simple discharge test are given.

The pressure losses in airlift are obtained by an analysis of the behavior of particles in consideration of resistance force due to collisions of particles with the pipe wall and are compared with experimental ones.

In addition, the drag coefficients of particles in the pipeline, which are required for the calculation of the pressure losses, are shown for a wide range of Reynolds numbers.

Main symbols used in the paper are as follows.

c ; particle velocity
 d_k ; mean diameter of particles
 d ; inner diameter of a pipe
 e ; gap between an air nozzle and an inner pipe of airlift, see Fig.1(b)
 F ; cross-sectional area of a pipe $=\pi d^2/4$
 Fr_f ; Froude number based on terminal velocity
 Fr ; Froude number based on air velocity
 g ; acceleration of gravity
 G_k ; mass flow rate of particles
 G_L ; mass flow rate of air
 k ; velocity ratio $=c/u$
 Δp ; pressure loss of air-solids mixture $=\Delta p_L + \Delta p_K$
 Δp_K ; additional pressure loss due to particles
 Δp_L ; pressure loss due to air flow alone
 t ; time
 u ; mean air velocity in a pipe
 w_f ; terminal velocity of particles
 x ; distance
 γ_K ; true specific weight of particles
 γ_b ; bulk specific weight of particles
 λ_K ; pressure loss coefficient due to particles
 μ ; solid loading ratio $= G_k/G_L$
 ρ_K ; density of particles $=\gamma_K/g$
 ρ_L ; air density
 ρ_{KF} ; mean density of particles in a pipe
 ϕ_i ; angle of repose
 ϕ ; shape factor of particles

2. Experimental apparatus and procedure

A scheme of the experimental setup and details of a mixing portion at the bottom of airlift tank are illustrated in Fig.1(a) and (b), respectively. Air flow from a turbo-blower is led to an air nozzle and it enters an inner pipe (6). In the actual

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pipeline systems the air conveys the particles throughout the pipeline, but in the tests the air is released into the atmosphere after a cyclone (8). Particles in the airlift tank (7) with a diameter of 280 mm were mixed at the gap between the air nozzle and the inner pipe, and were conveyed upward in the pipe to a measuring tank (12) through a cyclone (8) and receiver (9). The diameter of the air nozzle is equal to that of the inner pipe and a screen is installed under the air nozzle to prevent a reverse flow of the particles to a pipeline for air supply as shown in Fig.1(b).

The air flow was controlled with valves (1)~(3), and the air flow rate was measured with Pitot tube (4). The mass flow rate of the particles was measured with load-cell (11), strain meter and digital volt-meter.

Another apparatus in Fig.1(a) such as distributor (10), feeder (13), cyclone (14), tanks (15), (16) are the auxiliary equipments for the circulation of the particles.

In order to obtain the power required for airlift, the pressure distribution along the inner pipe axis was measured at

(a) Experimental setup

(b) Details of mixing portion

Fig.1 Test rig for the feeding test

12 stations as shown in Fig.2 with multi-tube manometer.

In the test mentioned above, the pipes of acrylate with diameters 30, 40 and 52 mm were used.

The mass flow rate of particles from a two-dimensional port, Fig.3, was determined to obtain the basic characteristics of the particle flow at the mixing portion of airlift. The storage tank is 350 x 350 mm in cross section with a port of 125 mm in width and 6 mm in height. In the tests, the weights of the particles flowing out from the port at the center of 100 mm in width were measured with a channel to avoid the end wall effects.

Particles used in the tests are polyethylene pellets listed in Table 1.

Fig.4 illustrates the test rig for the measurement of terminal velocities of particles in the turbulent flow in pipes. The test section consists of a vertical pipe of transparent acrylate 50 mm in diameter, 1100 mm in length. Air flow from a blower entered the vertical pipeline through a bend. In the pipeline, a honeycomb (5) and a screen (6) are installed to prevent

Fig.2 Measuring stations for pressure distribution measurement

① Slide valve	④ Adjustment plate for gap
② Storage tank	⑤ Channel
③ Particles	

Fig.3 Test rig for discharge test

Table 1 Physical properties of particles

		Pellet A	Pellet B	Pellet C
Mean diameter	mm	3.43	1.17	1.07
True specific weight	kg/m ³	969	980	980
Bulk specific weight	kg/m ³	570	615	617
Terminal velocity	m/sec	5.83	4.05	3.82
Angle of repose	deg	29	22	20
Configuration		cylindrical	spherical	spherical
Shape factor		1.19	1.00	1.00

Fig. 4 Test rig for the measurement of terminal velocity

a secondary flow due to the bend or a reverse flow of particles to the pipeline for air supply. Some of the particles put in the test section were carried over by the air velocity and collected by a receiver (7). The air velocity was controlled with a valve (1) and measured with Pitot tube (2) using a pressure transducer (8), a strain meter (9) and a volt-meter (10). The air velocities tested were (3-30) m/sec.

3. Feeding performance

3.1 Discharge test under the gravity force

It is natural to consider that the feeding performance of airlift is affected by the behavior of particles flowing out from a port or a gap. A discharge characteristic of particles under the gravity force will be discussed at first.

The behavior of particles near the port at the bottom of the storage tank can be analysed using the same treatment as that by Yokogawa(2). Fig. 5 indicates the cross section of two-dimensional port, where layer A is a dead region in which the particles are at rest, and the angle between the upper surface of layer A and the bottom

surface may be equal to angle of repose of the particles, ϕ_i . The solid line XX' denotes the direction of the principal stress of a layer of particles. Assuming that the particles in the outer region of XX' (i.e. left side of XX' in the figure) fall down along X'Y from XX' with no initial velocity due to the gravity force and the frictional force can be neglected, we can write the horizontal component of the particle velocity, v , at the distance x from X in the XY plane as

$$v = \sqrt{2gh} \cos \phi_i \quad (1)$$

where,

$$h = \frac{x}{1 + \frac{1}{\tan \phi_i \tan \theta}} \quad (2)$$

Then, mean velocity $\bar{v}$ over the XY plane yields

$$\begin{aligned} \bar{v} &= \frac{1}{e} \int_0^x \sqrt{2gh} \cos \phi_i dx \\ &= \sqrt{\frac{8g \cos^2 \phi_i}{9 \left(1 + \frac{1}{\tan \phi_i \tan \theta}\right)}} e^{2/3} \quad (3) \end{aligned}$$

Assuming that the specific weight of the particles in XY plane is equal to γ_b , mass flow rate of the particles from the two-dimensional port with a width b can be written as

$$W \propto b e \gamma_b \bar{v} = \sqrt{\frac{8 \cos^2 \phi_i}{9 \left(1 + \frac{1}{\tan \phi_i \tan \theta}\right)}} b \gamma_b \sqrt{g} e^{2/3} \quad (4)$$

From eq. (4), we get

$$e \propto \left(\frac{W}{b \gamma_b \sqrt{g}} \right)^{2/3} \quad (5)$$

Fig. 6 shows the relations between $(W/b\gamma_b\sqrt{g})^{2/3}$ and e obtained from the discharge test. In the figure b , W , γ_b and g are represented in mm, g/sec, g/mm³ and mm/sec², respectively. The values of $(W/b\gamma_b\sqrt{g})^{2/3}$ can be given in the linear relation as

Fig. 5 Flow of particles near the two-dimensional port

$$\left(\frac{W}{b\gamma_s\sqrt{g}}\right)^{2/3} = \alpha(e - \beta) \quad (6)$$

Values of α and β determined from the experiment are listed in Table 2. The value of β implies the limit clearance from which the particles can be discharged by the gravity force, which may be determined from the diameter, the shape factor and the friction factor of particles. In the study β is represented with ϕ and d_K as follows.

$$\beta = (0.78\phi + 1.42)d_K \quad (7)$$

where, the shape factor ϕ is defined as the ratio of the surface area of a particle to that of a sphere.

Fig.6 Mass flow rate from the two-dimensional port

3.2 Feeding test of airlift

The feeding test of airlift was made with a gap e of (15~50) mm and an air velocity in the inner pipe u of (10~30)m/sec. The mass flow rate of particles G_k (in kg/min) is given in Fig.7. As the feeding performance of airlift is complicated for various values of d , u and e , it is quite difficult to represent a general performance in a universal form. Roughly speaking, the feeding performance of airlift can be summarized as follows.

The influence of u on G_k is relatively small, and for u as low as the terminal ve-

Fig.7 Mass flow rate of particles in airlift

Table 2 Values of α and β in eq.(6)

	Pellet A	Pellet B	Pellet C
α	0.556	0.715	0.718
β mm	8.11	2.60	2.37

Table 3 Values of e_c (mm)

	Pellet A	Pellet B
$d=30$ mm	45	20
40 mm	40	20
52 mm	40	20

locity of the particles the feeding performances become unstable and the particles tend to choke in the inner pipe. The value of G_k becomes large as e increases but for too large e the pressure to fluidize the accumulated particles in the inner pipe becomes too high to start up the equipment.

3.3 Representation of feeding performance

A general relation between G_k and e obtained from the feeding tests can be summarized as shown in Fig.8.

In the range of e less than a certain critical value e_c (denoted by region II in the figure), G_k is affected by u to a small extent and G_k becomes large as u increases. In the range of e larger than e_c (region I in Fig.8), however, the influence of u on G_k can be neglected.

The critical values of e_c determined from the experiment are listed in Table 3. The values of e_c may be determined from the kind of material, i.e. from the diameter, the friction factor and the shape factor of the particles. For polyethylene pellets used in the tests, we obtained the relation

$$e_c = (43 - 26\phi)d_K \quad (8)$$

The feeding performance in the region I will be discussed. In the region, G_k is not affected by u , then it can be considered that G_k is determined by the mass flow rate of the particles discharged under the gravity force from the side surface of the gap (i.e. a cylindrical surface of d in diameter and e in height). Therefore, the results of a discharge test described above can be applied to the problem after a re-

Fig.8 General relation between G_k and e

Fig. 9 Feeding performance of airlift (region I)

placement of b by πd . Fig. 9 indicates the relation between $(W/\pi d \gamma_b \sqrt{g})^{2/3}$ and e , which shows that $(W/\pi d \gamma_b \sqrt{g})^{2/3}$ can be represented as a linear function of e satisfying $G_k = 0$ at $e = \beta$, where β is the critical value of e listed in Table 2. Therefore, the following relation holds in the region I.

$$\left(\frac{W}{\pi d \gamma_b \sqrt{g}}\right)^{2/3} = K_1(e - \beta) \quad (9)$$

The values of K_1 obtained from the feeding tests are 0.366 and 0.391 for pellet A and B, respectively. Coefficient α for the discharge test from a two-dimensional port (see Table 2) is different from K_1 , which can be explained from the fact that in contrast to the case of two-dimensional port the discharge surface of airlift is cylindrical and particles are discharged toward the center of the inner pipe. Such a process makes G_k smaller than that for the two-dimensional port. In consideration of the difference in the configuration of the discharge surface, α is modified from the experimental results as follows.

$$K_1 = 0.6\alpha \quad (10)$$

Fig. 10 Feeding performance of airlift (region II)

Then, in the region I (i.e. $e > e_c$) the mass flow rate of particles for airlift G_k (in kg/min) is given in the form

$$G_k = 0.06W = 0.06\pi d \gamma_b \sqrt{g} (0.6\alpha(e - \beta))^{3/2} \quad (11)$$

where, d and e are represented in mm and γ_b and g are in g/mm³ and mm/sec², respectively.

In the case of the inner pipe with a larger diameter than that used in the tests, the behavior of particles from the gap becomes quasi two-dimensional, then K_1 may approach the value of α .

Next, G_k in the region II will be discussed. In the region G_k increases gradually with an increase in u , which suggests that the fluid force cannot be neglected in comparison with the gravity force. Therefore, an analysis of the discharging performances in consideration of the fluid force is necessary, but this is too complicated to apply to a practical calculation. For simplicity, neglecting the effect of the fluid force on G_k as shown in Fig. 10 we put the feeding performances as

$$G_k = \frac{G_{kc}}{e_c - \beta} (e - \beta) \quad (12)$$

where, G_{kc} is defined by the value of G_k corresponding to $e = e_c$. In the calculation of G_k from the equations, e_c is obtained from eq. (8) at first, then G_{kc} from eq. (11), and G_k is given by eqs. (11) and (12) for $e \geq e_c$ and $e < e_c$, respectively.

Fig. 11 indicates the experimental results and the calculated ones from eqs. (8), (11) and (12), which shows that the feeding performances of airlift can be estimated by the procedure developed above with good accuracy for practical use.

4. Pressure losses

The power required, N , for airlift is obtained from eq. (13).

$$N = \frac{G_L}{g \rho_L} \Delta p \quad (13)$$

where,

$$\Delta p = \Delta p_L + \Delta p_R \quad (14)$$

Fig. 11 Comparison between experiments and calculation of G_k from eqs. (11) and (12)

The pressure losses due to air flow alone, Δp_L , can be estimated from many studies of pressure loss coefficients for single-phase flow, and the method to calculate Δp_K will be shown.

In contrast to the case of the vertical pipeline for pneumatic conveyance, the inner pipe of airlift is not long enough for the particles to reach their steady velocity in many cases. For such a problem, the method for calculation of the pressure losses with combined use of the equation of motion for particles and the momentum equation for air flow is more convenient than that of superposing an acceleration loss on the pressure loss in the steady velocity region(3)(4).

In addition, for the experiment on the pressure loss of the vertical pipeline a quite large test rig is necessary to get the additional pressure loss coefficient. In the present paper, the pressure loss coefficient is obtained using a relatively short pipeline.

4.1 Formulation

The flow is assumed to be two-dimensional, and the equation of motion for the particles in a small interval dx , Fig.12 (a), can be written as

$$\rho_{KF} F \frac{dv}{dt} = f_D - f_K - f_g \quad (15)$$

where, ρ_{KF} denotes the mean density of particles in dx , which yields

$$\rho_{KF} = \frac{G_K}{gF} = \frac{\rho_L}{k} \quad (16)$$

The drag force f_D can be represented using the terminal velocity of particles, w_f , as

$$f_D = \rho_{KF} g F \left(\frac{u - w_f}{w_f} \right)^2 dx \quad (17)$$

The resistance force due to collision between particles and pipe wall can be given by eq.(18) using the same treatment proposed by Weidner(5).

$$f_K = \lambda_K \frac{\rho_{KF}}{2} c^2 F \frac{dx}{d} \quad (18)$$

The gravity force f_g is

$$f_g = \rho_{KF} F dx g \quad (19)$$

Combining eqs.(17),(19) and (15), and normalizing eq.(20), we get eq.(21).

$$x \frac{d\tilde{z}}{d\tilde{z}} = \tilde{z} \left[1 - \lambda_K F_r f^2 / 2 = \tilde{z} \left[1 - (F_r f / F_r)^2 = \tilde{z} \right] \quad (20)$$

Fig.12 Flow in a vertical pipeline

$$\frac{dk}{d\tilde{z}} = \frac{1}{F_r f^2} \frac{\lambda k^2 - 2k + \tilde{z}}{k} \quad (21)$$

Integrating eq.(21) under the conditions $k=0$ at $\tilde{z}=0$ and $k=k$ at $\tilde{z}=\tilde{z}$, we have

$$\tilde{z} = \frac{F_r f^2}{2\lambda} \left[\ln \frac{\lambda k^2 - 2k + \tilde{z}}{\tilde{z}} + \frac{1}{\sqrt{1 - \lambda \tilde{z}}} \right] \\ \approx \ln \frac{\lambda k - 1 + \sqrt{1 - \lambda \tilde{z}}}{\lambda k - 1 + \sqrt{1 - \lambda \tilde{z}}} \frac{1 - \sqrt{1 - \lambda \tilde{z}}}{1 + \sqrt{1 - \lambda \tilde{z}}} \quad (22)$$

The velocity ratio in the steady velocity region, k_∞ , can be given from eq.(21) by putting $dk/d\tilde{z} \approx 0$.

$$k_\infty = \frac{\tilde{z}}{1 + \sqrt{1 - \lambda \tilde{z}}} \quad (23)$$

The additional pressure loss is obtained by applying the momentum equation to the air flow in dx , which yields

$$dp_K F = f_D \quad (24)$$

Combining eqs.(16),(17) and (24), we get

$$\frac{dp_K}{d\tilde{z}} = \frac{\rho_L u^2}{F_r f^2} \frac{(1-k)^2}{k} \quad (25)$$

Eliminating $\tilde{z}$ between eqs.(21) and (25), we can write

$$\frac{dp_K}{dk} = \rho_L u^2 \frac{(1-k)^2}{\lambda k^2 - 2k + \tilde{z}} \quad (26)$$

Integrating eq.(26) under the conditions $p_K = 0$ at $k=0$ and $p_K = \Delta p_K$ at $k=k$, we have eq.(28) after a normalization of eq.(27).

$$\Delta p_K = \Delta p_K + \rho_L u^2 \left[\frac{2}{\lambda} \left(k - \frac{k-1}{\lambda} \right) \ln \frac{\lambda k^2 - 2k + \tilde{z}}{\tilde{z}} + \frac{k^2 - (2+\tilde{z})k + 2}{2\lambda \sqrt{1 - \lambda \tilde{z}}} \right] \\ \approx \ln \frac{\lambda k - 1 + \sqrt{1 - \lambda \tilde{z}}}{\lambda k - 1 + \sqrt{1 - \lambda \tilde{z}}} \frac{1 - \sqrt{1 - \lambda \tilde{z}}}{1 + \sqrt{1 - \lambda \tilde{z}}} \quad (28)$$

The additional pressure loss in the steady velocity region can be obtained from eq.(25) by putting $k = k_\infty$.

$$\frac{dp_K}{d\tilde{z}} = \frac{\rho_L u^2}{F_r f^2} \frac{(1-k_\infty)^2}{k_\infty} \quad (29)$$

4.2 Additional pressure loss

In general, the additional pressure loss coefficient, λ_K , is determined from the experimental data in the steady velocity region. In the study, however, λ_K is obtained by comparing the pressure distribution calculated from eqs.(22) and (28) with experimental one by the method of least squares.

The values of λ_K are somewhat different for each pipe diameter and pellet, but the experimental pressure distribution can be represented with good accuracy by putting $\lambda_K = 0.0045$ as shown in Figs.13 and 14. In Fig.14, Δp_{Kc} and Δp_{Ke} denote the calculated and experimental pressure losses, which shows that the agreement is sufficiently good.

The additional pressure loss for different materials of pellet and pipe wall can be determined by the method described above using λ_K reported in the literature(6)(7).

4.3 Velocity ratio in the steady velocity region

As mentioned above, the pipeline used in the study is too short to obtain k_∞ , and the calculated value of k_∞ from eq.(23) is compared with the experimental one in the literature.

Fig.15 illustrates the comparison between

Fig.13 Comparison between experimental and calculated pressure losses

Fig.15 Comparison between experimental and calculated values of k_{∞}

calculated value and experimental one by Morikawa(6) with polystyrene pellets of $d_k=2.67$ mm, $\gamma_k = 1080$ kg/m³ and $w_f=7.8$ m/sec, which shows a quite good agreement.

5. Drag coefficient of spheres in a pipeline

In the calculation of the additional pressure loss, an accurate estimation of the terminal velocity of particles, w_f , is indispensable. In many cases the terminal velocity is estimated from the drag coefficient of a single sphere in a uniform flow. But the air flow in the pipeline is a fully developed turbulent flow in most cases and the velocity distribution is not uniform. Therefore, the terminal velocities of various kinds of spheres in the pipeline are obtained by the method proposed by Welschof (3).

When G_0 and G_1 denote the weight of particles put at first in the test section, Fig.4, and that of particles carried over from the test section till the air velocity reaches u , respectively, the carry over ratio of the particles $\eta = (G_1/G_0) \times 100(\%)$ becomes a function of u .

Fig.14 Comparison between experimental and calculated pressure losses

Fig.16 indicates the experimental results obtained with particles listed in Table 4. In the present study, w_f is defined as the air velocity at which η becomes 50. For air flow, the drag coefficient c_D can be written as

$$c_D = \frac{4}{3} \frac{\rho_K}{\rho_L} g \frac{d_K}{w_f^2} \quad (30)$$

The Reynolds number of a sphere in the air flow with velocity of w_f is

$$Re_w = w_f d_K / \nu \quad (31)$$

where, ν denotes the kinematic viscosity of air. Fig.17 gives the relation between c_D and Re_w , in the figure the solid line indicates c_D of a sphere in a uniform flow presented by Morsi & Alexander(9), and data ①~⑥ are experimental values by Flatow(7) and Siegel(8). In the region of $Re_w > 500$, c_D is different from that in the

Fig.16 Relation between carry over ratio and air velocity

Fig. 17 Drag coefficient of spheres in a pipeline

uniform flow and becomes about 0.61, and for $Re_w < 500$ C_D approaches the values in a uniform flow. In the figure, symbol $\triangle$ indicates the pellet A, which is used in the discharge test and has a cylindrical shape, and the drag coefficient is quite large.

6. Conclusions

The experimental and theoretical studies of feeding performance and pressure loss of airlift are described and the method for calculation of feeding capacity or the power required is shown.

The results obtained are summarized as follows.

(1) The feeding performance of airlift can be estimated by eqs. (8), (11) and (12). Some constants in the equations are obtained from simple tests.

(2) The additional pressure loss coefficient can be estimated from the data in the acceleration region and the procedure to calculate the pressure loss of airlift developed is sufficiently accurate for practical use.

(3) The terminal velocity and the drag coefficient of spheres in the pipeline are given in a wide range of Reynolds numbers.

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Table 4 Diameters and specific weight of particles

Pellet	Diameter mm	Specific weight kg/m ³
Polyethylene pellet	0.96	980
Polyethylene pellet	1.09	980
Polyethylene pellet	1.20	980
Polyethylene pellet	1.39	980
Polyethylene pellet A	3.43	969
Spherical pill	2.64	1378
Spherical pill	4.21	1287
Spherical pill	5.95	1475
Spherical clay	6.36	1625
Steel ball	3.16	7864
Steel ball	4.75	7836
Steel ball	6.37	7819