

REDUCTION OF POWER CONSUMPTION FOR PNEUMATIC CONVEYING OF WET GRANULAR MATERIALS

FUMIAKI TAKEUCHI

Okayama University, Administration Center for Environmental Science and Technology, 3-1-1, Tsushimanaka, Okayama 700

TAKESHI KANO

AMANO Co. Ltd., 275, Mamedo-cho, Kitaku, Yokohama 222

TOSHIAKI YAMADA

ASMO Co., Ltd., 390, Umeda, Kosai 431-04

TERUO TAKAHASHI

Department of Applied Chemistry, Okayama University, Okayama 700

Key Words: Powder, Wet Granular Materials, Pneumatic Conveying, Vibration, Liquefied-State, Power Consumption, Transport Efficiency

Pneumatic conveyance of wet granular material was investigated, focusing on the reduction of power consumption. Flow patterns at various water contents were modelled and the physical properties of particles as well as the conveyance pressure drop were measured for polystyrene pellet conveying. Effects of vibration conditions on the pressure drop and conveyance efficiency were investigated. Favorable water content and vibration conditions were found to reduce the power consumption. It was confirmed that liquefaction resulted from a multiplier effect of water addition and vibration and contributed considerably to reduction of power consumption and prevention of choking. The applicability of these results was confirmed with actual devices.

Introduction

Various substances are processed in granular form in recent advanced technologies. Pneumatic conveyance of granular materials has unique advantages compared with other systems and has been widely used in the industrial field.

However, the reduction of power consumption is strongly required, since it is much larger in pneumatic conveyance than in conventional methods.

Power consumption in flying particles or pneumatic conveyance of dry particles has been reported²⁻⁷⁾ in an extensive literature, but there were only a few papers in the case of wet particles.

To resolve this problem we have examined the effects of water content of wet granular materials upon pneumatic conveyance and of leading vibration to a conveying pipe upon the pressure drop of pneumatic conveyance.

Reporting results of experimental liquefaction of particles in a conveying pipe, this article presents effective information about the possibility of reducing power consumption.

1. Theory

The forces acting on a deposited wet particle bed

in conveyance are considered as shown in Fig. 1. A_1 is the cross-sectional area of a layer of air optionally containing flying particles. A_2 is the cross-sectional area of a water-containing particle layer associated with air flow. A_3 is the cross-sectional area of a layer comprising water and particles without air flow. R_s is the shearing force between air flow and flying particles. R_w is the friction between the conveying pipe wall and the deposited particle layer. P is the driving force of the particle layer. W is the force on the wall caused by the particles. The following equations are given with Δp as pressure drop in conveyance and R_a as air shearing force at the pipe wall of A_1 .

In the case of a deposited layer at rest:

$$\Delta p A_1 = R_s + R_a \quad (1)$$

In the case of a conveying deposited layer:

$$P = \Delta p (A_2 + A_3) + R_s = R_w \quad (2)$$

Void-based water saturation ϕ is employed as water content. ϕ_c is the critical water content. A wet particle bed shows water retention at a water content up to ϕ_c . ϕ_s is the saturated water content at $\phi = 1$. ξ_{wc} and ξ_{ws} are wall friction coefficients. C_c and C_s are adhesion strengths. (Subscript c means critical water content and s means saturated water content.)

The following equations are given about R_w , which

* Received December 2, 1991. Correspondence concerning this article should be addressed to F. Takeuchi.

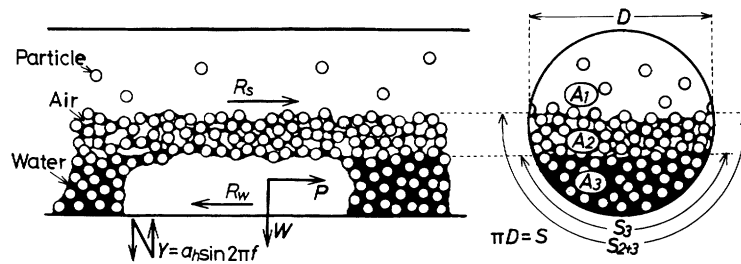


Fig. 1. Forces on particles including water

seems to be the dominating factor on Δp . ΔL is the conveying distance. S_{2+3} is the part of inner circumference S in contact the particle beds A_2 and A_3 . S_3 is part of S in contact only with A_3 .

$$R_w = W \left[\xi_{wc} \cdot \frac{S_{2+3} - S_3}{S_{2+3}} + \xi_{ws} \cdot \frac{S_3}{S_{2+3}} \right] + C_c(S_{2+3} - S_3)\Delta L + C_s \cdot S_3 \cdot \Delta L \quad (3)$$

$$W = \{\rho_s(1-\varepsilon) + \rho_w\varepsilon\}A_3g\Delta L + \{\rho_s(1-\varepsilon) + \rho_w\varepsilon\phi_c\}A_2g\Delta L \quad (4)$$

where ρ_s is particle density, ρ_w is water density, and ε is void fraction.

R_a is described as follows:

$$R_a = \tau_c (S - S_{2+3})\Delta L \quad (5)$$

τ_c is the shearing force of air flow:

$$\tau_c = (\lambda_a/4)(\rho_a \cdot u_a^2/2) \quad (6)$$

in which ρ_a is air density and u_a is air velocity. $\Delta p/\Delta L$ is calculated from Eqs. (1)–(6) (filled with physical properties of a test piece at ϕ_c and ϕ_s and the conveyance condition) based on the assumption that λ_a satisfies Blasius' equation.

$$\lambda_a = 0.316 Re^{-0.25} \quad (7)$$

2. Experimental apparatus and procedure

The wall friction coefficient ξ_w of a wet granular material was measured by an apparatus shown in Fig. 2. A vessel of 350 mm × 150 mm × 100 mm (depth) was filled with a granular material of controlled water content, in which an acrylic resin rolling drum of inner diameter 52 mm and length 300 mm was horizontally set. Rotation of the drum was caused by a weight settled inside, i.e. the weight was linked to another vessel containing water, whose amount was increased by water added from an injector. The moments of rotation were measured for cases of various initial weights. Thus, ξ_w was determined, being defined as [shearing stress]/[perpendicular stress]. As their linearity was confirmed, adhesion strength C was obtained by extrapolation of shear force at perpendicular stress = 0 in Coulomb's equation.

Measurement of the wall friction coefficient in a vibrating granular layer is also possible in this

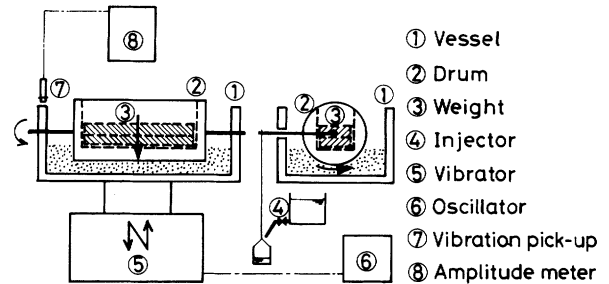


Fig. 2. Schematic diagram of apparatus to measure wall friction coefficient

Table 1. Physical properties of polystyrene pellet

Properties	Water content	$\phi=0$	$\phi=\phi_c=0.45$	$\phi=\phi_s=1.0$
Particle diameter	d_s [mm]	0.997	—	—
True density	ρ_s [kg/m ³]	1070	—	—
Bulk density	ρ_b [kg/m ³]	650	—	—
Coefficient of wall friction	ξ_w [—]	0.397	0.539	0.197
Cohesion	C [Pa]	0.153	0.397	0.105

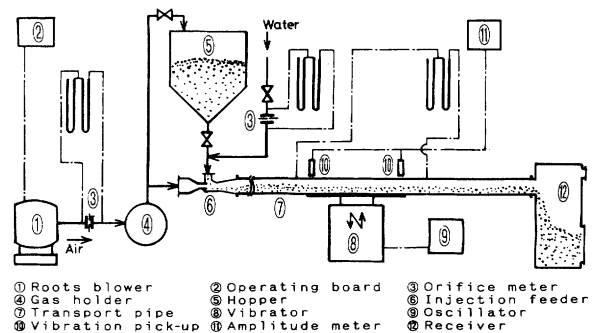


Fig. 3. Schematic diagram of experimental apparatus

apparatus. Polystyrene pellets are used in this study and their physical properties are shown in Table 1.

An outline of an experimental apparatus for pneumatic conveyance of wet granular material is shown in Fig. 3.

The apparatus consisted of a power section, a flow-measuring section for air and water, a particle-feeding section, a conveying pipe section, a vibrator section, an amplitude-measuring section, and a particle recovery section. The pipe of inner diameter $D=52$ mm and length of 4500 mm was prepared from

a transparent acrylic resin. A vibrator (3–150 Hz) was attached to the pipe and amplitude was measured by a non-contact meter.

The experimental procedure was as follows. A granular material was supplied to the pipe from a hopper. The flow control valves for air and water were set to settle an air velocity u_a and ϕ . Pressure drop Δp in $\Delta L = 1$ m conveyance and the condition of a particle bed, e.g. height of particle bed h , etc. were measured and photographs were taken at a stationary state. Then, perpendicular vibration was applied to the horizontal pipe and frequency f and half-amplitude a_h were measured at the stationary state.

The experimental condition is shown in Table 2. Lower u_a , e.g. in an area of sliding flow or an area of deposition flow, was settled.

3. Experimental results and discussion

3.1 Conveyance pattern

The flow patterns corresponding to different water contents of granular materials were investigated by their comparison for pipes at rest and pipes under vibration in the case of constant M_s and u_a values. An example is shown in the photograph in Fig. 4, where Λ is the vibration acceleration ratio $= a_h(2\pi f)^2/g$.

(1) Dry condition

At $\phi = 0$, particles flow over the surface of the deposited bed at rest. The depth (h) of the deposited bed increased when u_a was small. Under vibration applied to the pipe, h was reduced as a result of conveyance of the rest bed. Pressure drop was reduced.

(2) Water-unsaturated condition

At $\phi \approx 0.5$, wet particles flow over the surface of the deposited bed at rest and having irregular depth and waved surface. When u_a was beyond a critical velocity, the deposited bed was conveyed in the form of rock or plug. Under vibration, the rest bed showed smooth conveyance, reduction of h , and reduction of pressure drop.

(3) Water-saturated condition

At $\phi \approx 1.0$, the deposited bed flew slowly. Wet particles flew over the surface and showed adhesion onto the upper pipe wall. The flow rate of the bed increased under vibration.

(4) Water-supersaturated condition

At $\phi \approx 1.5$, most of the granular material was submerged in the water layer and was driven by water flow to show smooth conveyance on the bottom of the pipe. Under vibration the flow pattern hardly changed, whereas the flow rate of the deposited bed increased.

3.2 Change of pressure drop corresponding to water content

Figure 5 shows an example of the relationship between $\Delta p/\Delta L$ and ϕ . The solid line was drawn by using the calculated value from Eqs. (1)–(7). The

Table 2. Experimental conditions

Mass flow rate of particles	M_s [kg/s]	0.04
Velocity of conveying air	u_a [m/s]	3–9
Water content	ϕ [—]	0–1.5
Frequency of vibration	f [s ⁻¹]	40–80
Acceleration ratio $= a_h(2\pi f)^2/g$	Λ [—]	0–5
Direction of vibration		Vertical

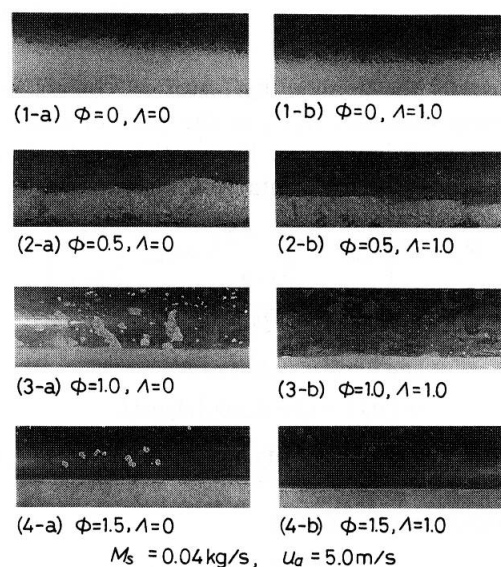


Fig. 4. Conveying conditions for different water contents

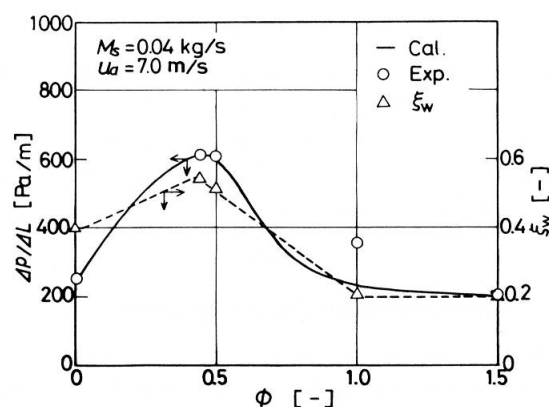


Fig. 5. Relationship between pressure drop and water content

calculated value showed close similarity to the experimental value. The value of ξ_w at each ϕ is also shown. The maximum $\Delta p/\Delta L$ was obtained at $\phi \approx 0.5$. The value decreased as ϕ increased and the pressure drop at $\phi \approx 1.5$ was smaller than that in dry condition. This phenomenon may deeply depend on the change in ξ_w , i.e. the wear resistance between the deposited bed and the pipe wall. A larger experimental value of $\Delta p/\Delta L$ compared with the calculated value was obtained at $\phi = 1 = \phi_s$. This is explained in that, because of the transition state, the real condition of the conveyance was $\phi < \phi_s$. Close similarity of

calculated value and experimental result was shown at $\phi \approx 1.5 \geq \phi_s$.

Thus, this analysis is applicable to the mechanism of a 3-phase flow comprising solid, gas, and liquid phase.

3.3 Effect of controlled water content and vibration on reduction of conveyance power consumption

In pneumatic conveyance of wet granular material, effects of controlled water content and vibration applied to a conveying pipe upon the pressure drop were examined. The relationship between $\Delta p/\Delta L$ and Λ is shown in Fig. 6. $\Delta p/\Delta L$ of $\phi=0.5$ and $\phi=1.0$ are larger than those of $\phi=0$ and $\phi=1.5$. At $\phi=1.5$ and $\Lambda=3$, the reduction of pressure drop is 40% of the total pressure drop of vibration-free conveyance of the dry material. The reduction of pressure drop is 20% at higher Λ , e.g. at $\Lambda=5.9$. These phenomena are thought to be the result of liquefaction under the multiple effect of water control and vibration.

The test particles in this study were globular and water-hydrophobic material. Further effects of controlled water content and vibration are expected on nonspherical and water-absorbing granular materials of larger ξ_w .

3.4 Influence of frequency on vibration effect

The conveyance efficiency η , which is defined as [work of conveyance]/[work consumption], is given for convenience:

$$\eta = \frac{M_s \cdot g \cdot \Delta L}{\Delta p \cdot Q_a \cdot \Gamma} \quad (8)$$

$$\Gamma = (N_e + N_v)/N_e \quad (9)$$

where Q_a is the volumetric flow rate of air, N_e is the blower's power consumption, and N_v is the power consumption of the vibrator.

The relationship between η_v/η_0 (subscript 0 means no vibration, v means vibration) and frequency f , which represents improvement of efficiency corresponding to vibration, is shown in Fig. 7. Reasonable improvement of efficiency at appropriately controlled water content and vibration is suggested by the results. Vibration is effective because N_v is far smaller than N_e and $\Gamma \approx 1$. Smaller f was favorable in this study, a situation similar to the case of dry powder.

Conclusion

The flow of pneumatic conveyance of wet granular material under controlled water content and vibration was investigated and the conclusions below were obtained.

(1) When the water content of transported particles was lower than the critical content, the power consumption increased with increase of water content. When the content was above the critical content, the conveyance required decreasing power as water

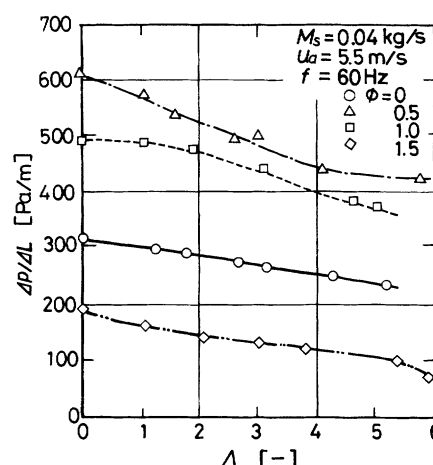


Fig. 6. Relationship between pressure drop and acceleration ratio

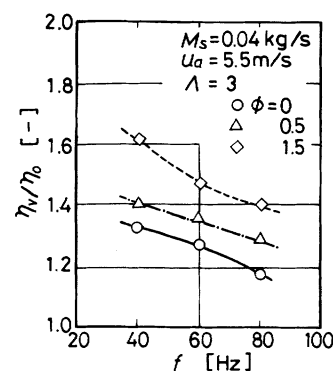


Fig. 7. Relationship between transport efficiency ratio and frequency of vibration

content increased. The relation showed good similarity to the result of calculation based on a model. The wall friction coefficient and the adhesion strength were dominating factors.

(2) Reduction of pressure drop in the pneumatic conveyance was possible by water content control and vibration. The pressure drop was reduced to 20% at vibration acceleration ratio=6 and water content=1.5 compared with the case of the dryness and no vibration.

(3) Significant vibration effect was shown at small frequency at a settled vibration acceleration ratio.

The result of this study is expected to be applied to actual wet-particle conveyance. Especially, the vibration effect is expected on part of the large pressure drop in a pipe which is easily choked.

Acknowledgement

Assistance with the experimental work was provided by Masayuki Suzuki and Akira Ogawa in the Department of Chemical Engineering, Sizuoka University.

Nomenclature

A_1 = cross-section area of a layer of air optionally containing flying particles [m²]

A_2	= cross-section area of a water-containing particle layer associated with air flow	[m ²]
A_3	= cross-section area of a layer comprising water and particles without air flow	[m ²]
a_h	= half-amplitude of vibration	[m]
C_c	= adhesion strength of critical water content	[Pa]
C_s	= adhesion strength of saturated water content	[Pa]
f	= frequency of vibration	[Hz]
g	= gravitational acceleration	[m/s ²]
h	= height of particle bed	[m]
ΔL	= length of transport test pipe	[m]
M_s	= mass flow rate of particles	[kg/s]
N_e	= power consumption of blower	[kW]
N_v	= power consumption of vibrator	[kW]
P	= driving force of particle layer	[N]
Δp	= pressure drop at ΔL	[Pa]
Q_a	= volumetric flow rate of air	[m ³ /s]
R_a	= air shearing resistance	[N]
R_s	= shearing resistance between air flow and flying particles	[N]
R_w	= friction resistance between pipe wall and deposited particles layer	[N]
S	= inner circumference = πD	[m]
S_{2+3}	= inner circumference in contact with layer of A_2 and A_3	[m]
S_3	= inner circumference in contact with layer of A_3	[m]
u_a	= air velocity	[m/s]
W	= force to the pipe wall in Eq. (4)	[N]

F	= ratio of additional power consumption by vibrator	[—]
ε	= void fraction	[—]
η_0	= transport efficiency in static state	[—]
η_v	= transport efficiency in vibrating state	[—]
A	= acceleration ratio = $a_h(2\pi f)^2/g$	[—]
ξ_{wc}	= wall friction coefficient of critical water content	[—]
ξ_{ws}	= wall friction coefficient of saturated water content	[—]
ρ_s	= particle density	[kg/m ³]
ρ_w	= water density	[kg/m ³]
ϕ	= water content	[—]
ϕ_c	= critical water content	[—]
ϕ_s	= saturated water content	[—]

Literature Cited

- 1) Akiyama, T., T. Naito and T. Kano: *Powder Technol.*, **45**, 215 (1986).
- 2) Kano, T., F. Takeuchi, E. Yamazaki and H. Tsuzuki: *Kagaku Kougaku Ronbunshu*, **7**, 127 (1981).
- 3) Kano, T., F. Takeuchi, Y. Kondo, M. Utumi, T. Maeda and K. Takemura: *Kagaku Kougaku Ronbunshu*, **9**, 477 (1983).
- 4) Kano, T., M. Utsumi, F. Takeuchi, H. Kuroyanagi and H. Kawade: *Kagaku Kougaku Ronbunshu*, **10**, 568 (1984).
- 5) Takeuchi, F., T. Kano, R. Aiura and N. Shibata: *Kagaku Kougaku Ronbunshu*, **12**, 97 (1986).
- 6) Takeuchi, F., T. Kano, T. Yamada and T. Maeda: *Kagaku Kougaku Ronbunshu*, **12**, 102 (1986).
- 7) Takeuchi, F., K. Kano, S. Yamada, S. Fukuda and K. Yamanaka: *Kagaku Kougaku Ronbunshu*, **11**, 674 (1985).