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Dedicated to Professor Dr.-Ing. E. Bahke on his 65th birthday

Pneumatic Transport in Dilute and Dense Phase

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Summary

The hydraulic transport of solids can be divided into two broad regions, dilute phase and dense phase. The author reviews the characteristics of these two cases and the relationships which describe them. Results of recent experiments are presented which should lead to a deeper understanding of this complex topic.

Nomenclature

c	average particle velocity	m/sec
c_w	drag coefficient in a cloud	—
c_{wf}	drag coefficient of a single particle	—
d	internal pipe diameter	mm
d_p	particle equivalent diameter	mm
$Fr = v/\sqrt{d \cdot g}$	Froude-Number ref. to air velocity	—
$Fr^* = c/\sqrt{d \cdot g}$	Froude-Number ref. to particle velocity	—
$\dot{G}$	solid mass flow rate	kg/sec
g	acceleration due to gravity	m/sec^2
K	factor	—
ΔL	pipe length	m
N	power	Nm/sec
Δp	pressure drop	N/m^2
$\dot{Q}$	air mass flow rate	kg/sec
w_f	fall velocity of a particle in a cloud	m/sec
w_{fo}	fall velocity of a single particle	m/sec
$\beta = w_f/v$;		
$\beta_o = w_{fo}/v$	velocity ratio	—
χ, δ	exponents	—
λ_L	resistance factor of air in a clean pipe	—
λ_Z	additional pressure drop factor due to the solids	—
λ_Z^*	friction factor	—
$\mu = \dot{G}/\dot{Q}$	mass load ratio	—
ϱ_L	density of air	kg/m^3

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1. Introduction

Thousands of years ago when the invention of ceramics in the Middle East began, one needed to replace the unreliable wind with a continuous air stream for heating.

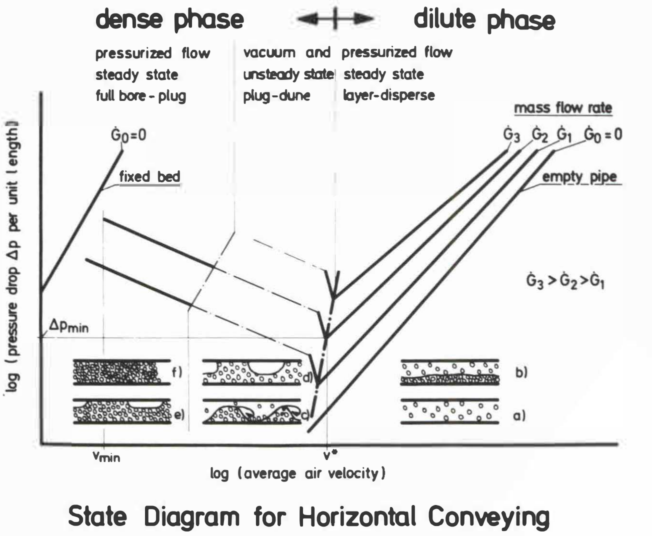
The ancient Egyptians, for example, used primitive air blowers in the iron ore process in order to attain high temperatures. These blowers and man-driven ventilators were in operation for a very long time. In the XVth century ventilators were used for aeration purposes in mines. Despite the technical use of a generated air flow for thousands of years, the conveying of solids by means of air flow energy was first utilized at a later date, although this possibility of conveying has been known a long time, e.g., in nature air can attain very high velocities such as cyclones, which are able to lift and transport heavy objects. With the invention of fast revolving and powerful engines the generation of similar air velocities was used for technical purposes. The first conveying line was set up in 1887 to transport agricultural products. Since that time, this process has been developed and found wide application in industry. It has become indispensable for plants which handle bulk solid materials.

2. Conveying Phases and State Diagram

The pneumatic conveying of Gas/Solids can be separated into two main areas, when referring to the mass load ratio, namely the dilute and dense phases.

The dilute phase is characterized by relatively high velocities and low mass load ratios. The flow is quasi-stationary and the pressure drop per unit length is low (Figs. 1 a and b). On the other hand the distinguishing characteristics of the dense phase are low velocities and high mass load ratios, in connection with high pressure drops. The dense phase begins with a rather quasi-nonstationary flow and then, when reducing the gas velocity, it goes smoothly over to a stationary flow zone. In the first phase, the pressure drop fluctuates as a consequence of the build-up and breakdown of solid dunes and plugs (Fig. 1).

The transition from the dilute phase to the dense phase is described by the pressure minimum curve. This curve connects all the minima of each mass flow rate in the state diagram (Fig. 1). The pressure minimum curve depends mainly on the particle size and shape, and pipe material. The pressure minimum curves for plastic materials have been dis-



Product	*Styropor - 3*
Particle size	d_p = 2,385 mm
Density	ρ_p = 1050 kg/m³
Pipe diameter	d = 52,6 mm
Pipe material	stainless steel
Average pipe wall roughness	R = 6 ÷ 10 µm

Fig. 1: Diagrammatic representation of the phase diagram for pneumatic conveying

cussed in detail in a previous paper [13]. Fig. 2 shows the relationship between the pressure drop per unit length $\Delta p/\Delta L$ and the average air velocity, with the mass flow rate as para-

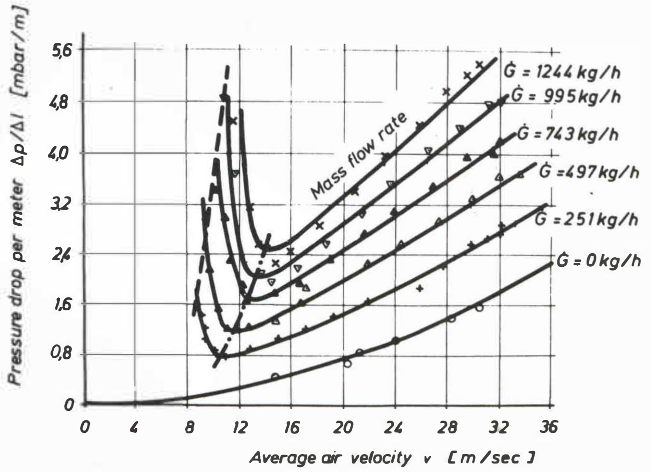


Fig. 2: State diagram: Pressure drop per unit meter versus average air velocity for various solid flow rates

meter, and the pressure minimum curve. A comparison of pressure minimum curves for different particle sizes and pipe materials is shown in Fig. 3. In this representation the mass load ratio μ is shown on the ordinate and the Froude-Number Fr on the abscissa in a double logarithmic scale.

An approximation of the pressure minimum curve in a dimensionless form is given in the following equation [13]:

$$\mu = \frac{1}{10^{\delta}} \, \mathrm{Fr}^{\chi} \qquad (1)$$

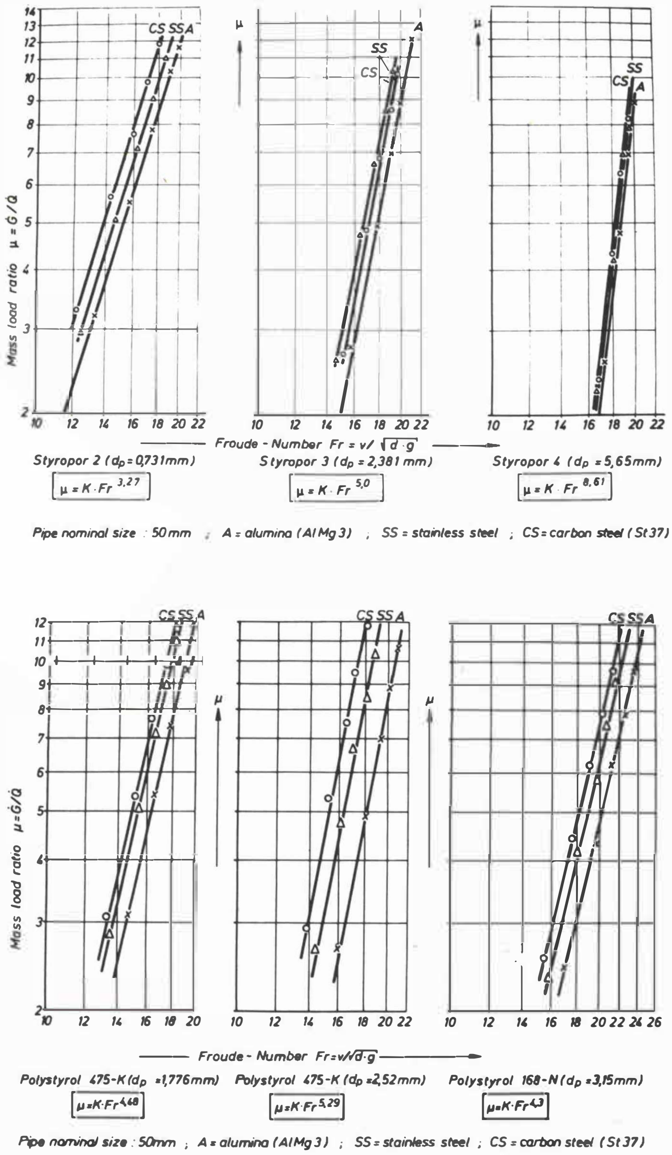


Fig. 3: Pressure minimum curves for Styropore and Polystyrole. Mass flow rate versus Froude-Number for various pipe materials and particle sizes

The exponents δ and χ which describe the pressure minimum curve are dependent on the particle size and the pipe material for bulk solids with a constant density. The graphs in Fig. 4 demonstrate this connection for plastic materials with a density of 1,050 kg/m³.

The representation of the mass load ratio against the Froude-Number with the parameters solid mass flow rate and pipe diameters (d = 50—400 mm) is shown in Fig. 5. Data out of the literature (Siegel [12]) and the author's own results were fitted together in this graph. The average pressure minimum curve for polystyrole with a particle size d_p = 1—2.5 mm can be approximated by the equation $\mu = K\,\mathrm{Fr}^4$. The deviation of the pressure minimum-points related to the Froude-Number is ± 15%.

This connection demonstrates very clearly that the characteristic numbers of similarity, Froude Fr und mass load ratio μ, represent the main influences in the pressure minimum zone for different pipe materials. Therefore the knowledge of the relation between the Froude-Number and the mass load

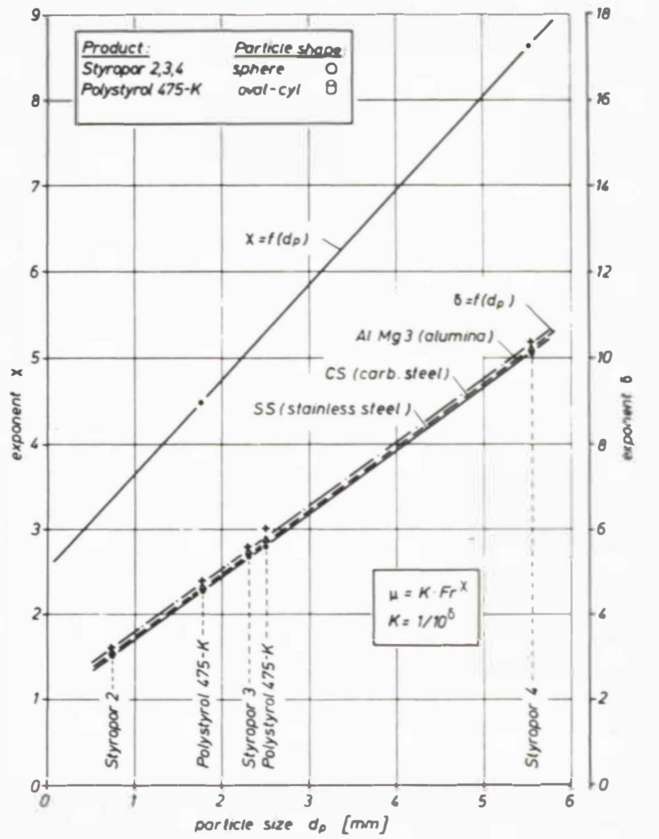


Fig. 4: Exponent χ and δ as a function of the particle size and pipe material

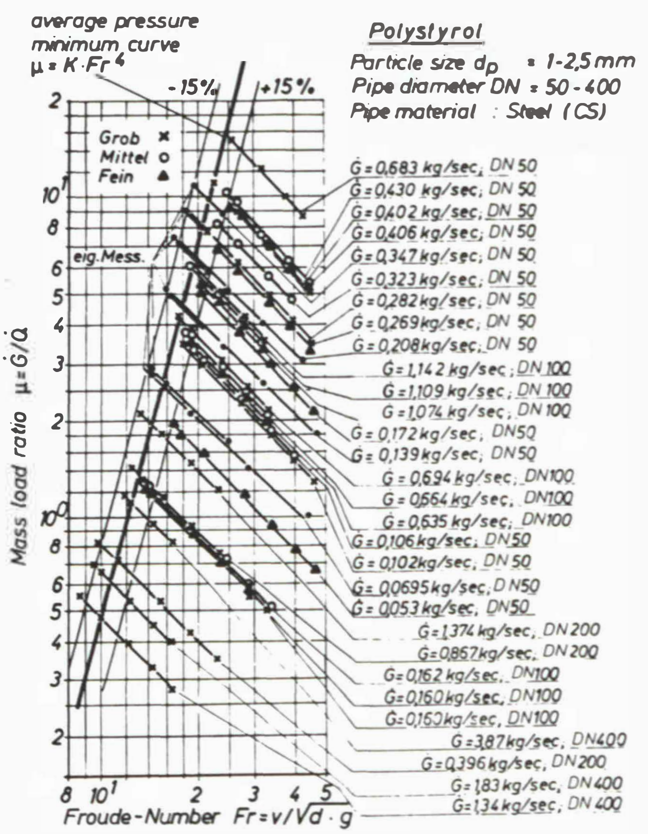


Fig. 5: Mass load ratio versus Froude-Number for various solid mass flow rates and pipe diameters particularly in the region of pressure minimum

ratio is indispensable for the layout of pneumatic conveying systems.

For a given particle size of a bulk material the designer of pneumatic plants is able to draw the pressure minimum curve. With that, one is able for an assumed mass load ratio, to determine the appertaining Froude-Number for the optimal operating condition in the dilute phase. From this one can calculate the pipe diameter for a defined mass flow rate and the corresponding average least start velocity and the air volume rate.

3. Operating Point and Plug Boundary

The blower respresents the main part of a pneumatic system. The safe running of a plant depends upon the blower selected and its characteristics. Fig. 6 demonstrates schematically two blower's characteristics and that of different mass flow rates for a conveying line. The main features of the curves at constant mass flow rates is clearly defined by the pressure minimum Δp_{min} and the absolute least velocity v_{min} at which transportation is still possible. To each blower characteristic corresponds a maximum mass flow rate of bulk solids.

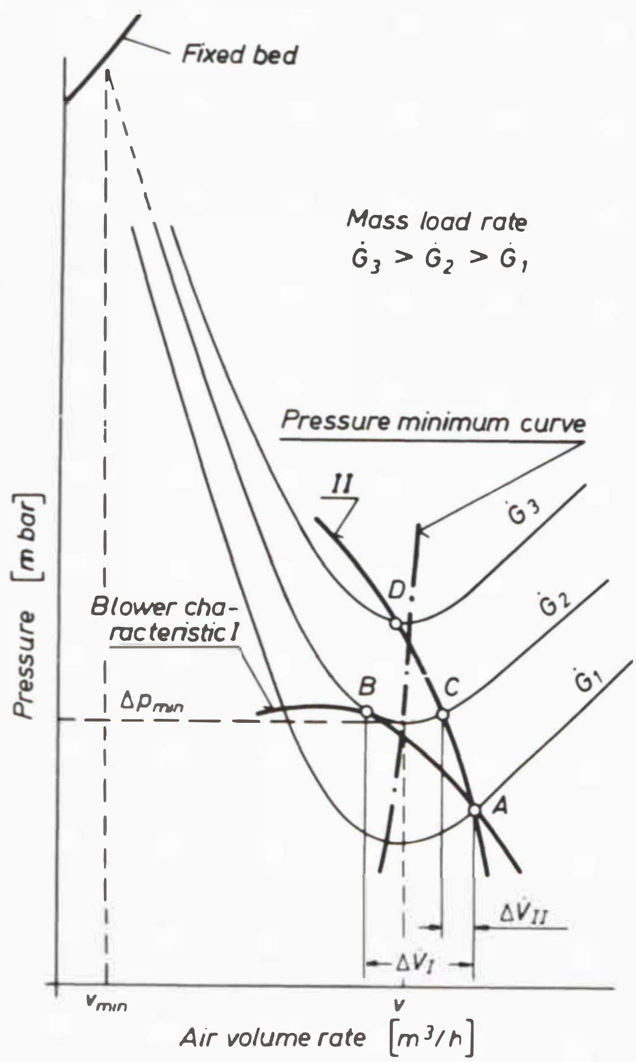


Fig. 6: Diagrammatic representation of blower and solid mass flow characteristics

For given blower characteristics I and II (Fig. 6) point A should be the operating point of a conveying system. Since the increase of the solid mass flow rate is bound to a rise in the resistance of the system, the working point A shifts either to point B on curve I or to point C on curve II. With this process the increase of pressure drop is combined with a throttling of the air volume throughput $\Delta \dot{V}$. Here, in this example the throttled air volume $\Delta \dot{V}_I$ is markedly greater than $\Delta \dot{V}_{II}$ on the second curve II (Point C). The new adjusted operating point B lies on the left hand side of the pressure minimum curve, i.e., in the unstable conveying zone (high pressure fluctuations) and in addition this point lies at the vertex of the blower's characteristic. The point B and the blower curvature I define the maximum mass load rate $\dot{G}_2$. It is not possible to convey a higher mass load rate with the blower characteristic I.

The risks of deposition and plugging of the line are very high. The least disturbance in conveying can block the whole system. In comparison, the other blower characteristic, curve II point C, has enough pressure in reserve to cope with any oscillation of the feeding device.

The plug boundary was firstly analysed by Segler [2] in 1934. Segler defined the begin of deposition of the solid particles in the pipe with the starting of the plug boundary. The stability of a conveying system depends primarily upon the option of the blower characteristics. Deposition of solids in the pipe is no risk at all as long as a steep characteristic curve of the blower is available.

4. Pressure Drop for the Horizontal Duct

In order to calculate the power consumption of the fan, one needs the total pressure drop of the system. The product of the pressure drop and air volume rate leads to the following equation:

$$N = \Delta p \cdot \dot{V} \tag{2}$$

This pressure drop is made up of different pressure losses as follows:

$$\Delta p = \Delta p_{\text{transport}} + \Delta p_{\text{separator}} + \Delta p_{\text{armatures}} \tag{3}$$

The total pressure drop, $\Delta p_{\text{transport}}$, consists of pressure drop parts, such as Δp_L for the clean air, Δp_B for the acceleration of the solids, Δp_{SR} the pressure drop for friction and impact, Δp_G the pressure drop for lifting and suspending the particles in the horizontal and vertical ducts as well as Δp_K the pressure drop for the pipe bends.

$$\Delta p_{\text{transport}} = \Delta p_L + \Delta p_B + (\Delta p_{SR} + \Delta p_G)_{\text{horizontal}} + (\Delta p_{SR} + \Delta p_G)_{\text{vertical}} + \Delta p_K \tag{4}$$

In a steady flow state, i.e., $\Delta p_B = 0$, in a horizontal line:

$$\Delta p = \Delta p_L + (\Delta p_{SR} + \Delta p_G) \tag{5}$$

$$\Delta p = \Delta p_L + \Delta p_Z \tag{6}$$

$$\Delta p = (\lambda_L + \mu \cdot \lambda_Z) \frac{\varrho_L}{2} \cdot v^2 \cdot \frac{\Delta L}{d} \tag{7}$$

Equation (7) from Barth et al. has been used and proved to be reliable. In this equation λ_L and λ_Z stand for the pressure drop coefficients for the air and for the solids, $\mu = \dot{G}/\dot{Q}$ the mass load ratio, ϱ_L the air density, v the air velocity, ΔL the pipe length and d the internal pipe diameter. The additional pressure drop coefficient λ_Z takes into consideration the influence of impact and friction as well as the influence of the particle weight.

The balance of energy in a control volume permits the separation of the additional pressure drop coefficient λ_Z into two terms as follows:

$$\lambda_Z = \lambda_Z^* \cdot \frac{c}{v} + \frac{2\beta}{\frac{c}{v}\,Fr^2} \tag{8}$$

λ_Z^* is the coefficient of impact and friction and c/v the velocity ratio of solid/gas. The second term of the sum takes into consideration the influence of the weight.

The balance of power on a particle cloud in a control volume yields the next equation:

$$\frac{c_W}{c_{Wf}} \left[\frac{v-c}{w_f}\right]^2 = 0.5\,\lambda_Z^*\,Fr^{*2} + \beta \tag{9}$$

From Equations (8) and (9) one obtains the particle fall velocity in a cloud:

$$w_f = \left[\frac{c_W}{c_{Wf}} (v-c)^2 \frac{2\,c/v}{\lambda_Z \cdot Fr^{*2}}\right]^{0.5} \tag{10}$$

On the assumption that w_f is different from the single particle fall velocity w_{fo} in still air, an attempt can be made to calculate this difference:

$$w_f = K\,w_{fo} \tag{11}$$

From Equations (10) and (11) one can evaluate K easily

$$K = \left[\frac{c_W}{c_{Wf}} \left(\frac{v-c}{w_{fo}}\right)^2 \frac{2\,c/v}{\lambda_Z \cdot Fr^{*2}}\right]^{0.5} \tag{12}$$

The value of β, the second additive term of Eqs. (8) and (9) which takes into consideration the influence of the weight, can be evaluated by means of experimental data.

$$\beta = w_f/v \tag{13}$$

$$\beta = \left[\frac{c_W}{c_{Wf}} \left(\frac{v-c}{v}\right)^2 \frac{2\,c/v}{\lambda_Z\,Fr^{*2}}\right]^{0.5} \tag{14}$$

The factor λ_Z^* which regards the impact and friction of the solid particles in the dilute phase, can be calculated with the transformed Eq. (8) as follows:

$$\lambda_Z^* = \left[\lambda_Z - \frac{2\beta}{\frac{c}{v}\,Fr^2}\right] \frac{1}{c/v} \tag{15}$$

5. Results of New Experiments

5.1 Conveying in the Dilute Phase

An anomaly has been found when measuring the pressure drop of the fine powder, sodium bicarbonate ($d_{p50\%}$ = 195 μm) in a stainless steel pipe. The results of these experiments are demonstrated in Fig. 7. At first the pressure drop decreases with increasing mass flow rate, and then after exceeding a certain rate (for clarity not drawn) it begins to rise normally.

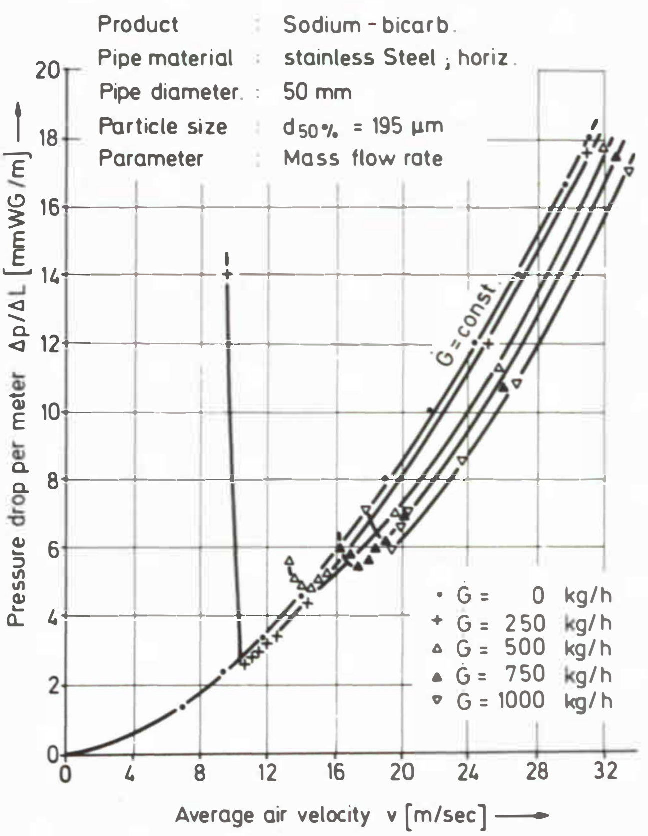


Fig. 7: State diagram: Pressure drop per unit meter versus average air velocity for various mass flow rates

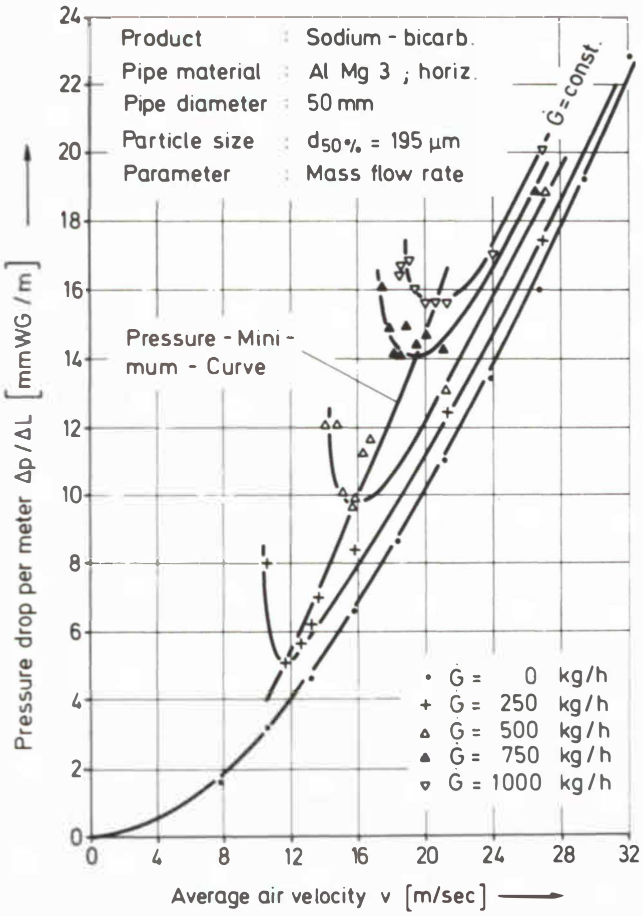


Fig. 8: State diagram: Pressure drop per unit meter versus average air velocity for various mass flow rates

It is probable that in this case the turbulence of the air flow is damped because of the motion of the fine particles. It is not incorrect to assume that in this special flow pattern the solid particles segregate. Earlier experiments have demonstrated the possibility of conveying fine particles in a segregated form even at high velocities. Results with the same product in an alumina pipe (Al Mg 3) are shown in the state diagram, Fig. 8. Contrary to the experiments run in the stainless steel pipe the pressure drop rises with increasing mass flow rate as expected.

The conveying of fine particles (dust) can show a non uniform behaviour, which does not correspond to the theory dealt with earlier; an explanation of this phenomenon is not yet available.

5.2 Dense Phase Conveying

The transition from dilute phase to dense phase conveying is very smooth, so that there is no clear limit in the state diagram (Fig. 2). On the left hand side of the pressure minimum curve is almost the end of the quasi-stationary flow of the dilute phase in the form of moving dunes. This phase changes into a plug flow when decreasing the air velocity. In exceptional cases it is possible to have a continuous plug flow all through the line at extreme low velocities, which dissolve then into shorter ones.

It has been proved by many researchers, for example, Welschof [6], Schröter [9] that it is very hard to maintain a continuous plug flow, i.e., one moving plug in the pipe. The plugs in the line allow only positive pressure forces on themselves. In consequence of the gas expansion, however, negative pressure forces affect the plugs, which reduces the plug length. In this phase of conveying, the plugs are subjected to continuous build-up and reduction in length.

The processes in the dense phase are more complex than in the dilute phase. A theoretical investigation of the high fluctuation of pressure and the variability of the solid concentration is difficult, therefore one still depends on empirical data. A systematic investigation has been untertaken in a pilot plant in order to obtain technical data and to work out fundamental relationships.

The experiments were performed with a blow tank system as shown in Fig. 9. Two means for the supply of the conveying air have been tested:

a) Swirl nozzle
b) Center nozzle in blowtank and an equalized pressure.

Contary to dilute phase conveying, which is characterized by a constant feed of solids, this rather important condition is lacking in the dense phase. One can therefore only determine the relationship between the mass flow rate of the bulk

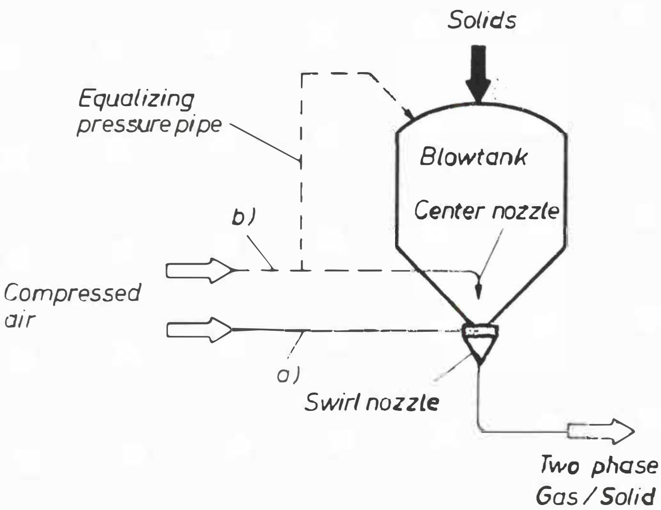


Fig. 9: Diagram of test blow tank

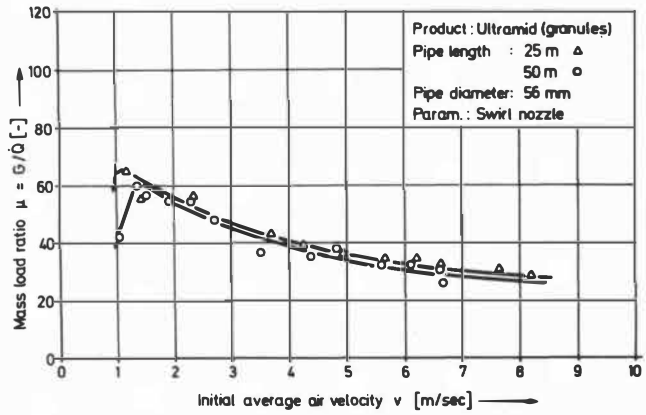


Fig. 11: Mass load ratio versus average air velocity

solid and the average initial air velocity. The first results obtained by means of the swirl nozzle, with no pressure equalization, demonstrate a gravitational flow out of the blow tank (Fig. 10). The mass flow rate increases at first very fast with increasing air velocity (curve a) and then becomes almost independent of the air speed. The second curve, (b) (center nozzle and equalized pressure) indicates a slightly accelerated flow of the solids with an equalized pressure on top of the blow tank.

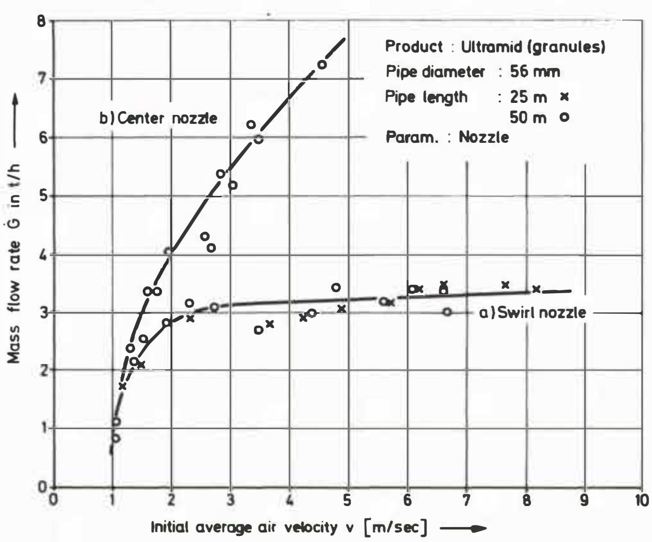


Fig. 10: Mass flow rate as a function of the average air velocity

These initial experiments demonstrate that through a suitable use of the gas flow energy an essential increase in the mass flow capacity of the bulk solid material can be attained. The dependency of the mass load ratio on the average initial air velocity is given in Fig. 11. For the first test condition (a) (swirl nozzle) the highest mass load ratio for the plastic granules was $\mu = 60$ at a velocity of about $v = 1.5$ m/sec. With increasing velocity a continuous fall of the mass load ratio was obtained ($\mu = 30$ at $v = 8$ m/sec.) For the second test condition the mass load ratio of $\mu = 50$ could be held constant until $v = 7$ m/sec in the 25 m line. The influence of the pipe length in Fig. 12 is clear. It shows that with increasing length the self adaption of the mass load ratio takes place, i.e., low values of μ.

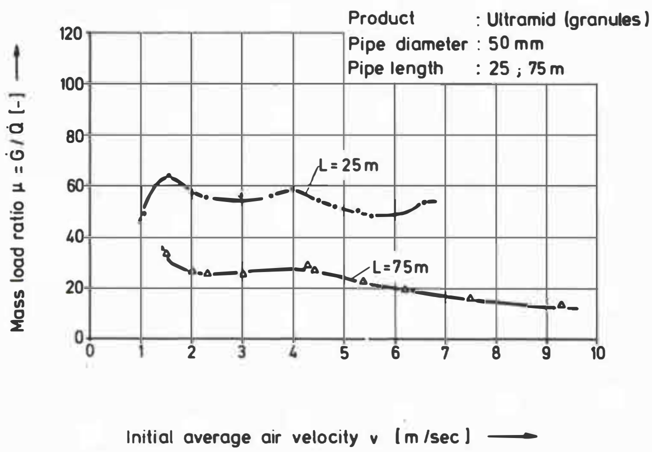


Fig.12: Influence of the pipe length upon the mass load ratio

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