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Principles of Hydraulic and Pneumatic Conveying in Pipes

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Grundlagen der hydraulischen und pneumatischen Rohrförderung
Principes du transport pneumatique et hydraulique par pipelines
Principios del transporte hidráulico y neumático por tuberías
パイプによる水・空気を利用しての運搬の原理
管道中液压和气压输送的原理
قواعد النقل بالناقلات الهيدروليكية والناقلات التي تعمل بالهواء المضغوط في فرنسا

Grundlagen der hydraulischen und pneumatischen Rohrförderung

Ein umfassender Überblick wird gegeben über die grundlegende Technologie und über die wesentlichen Dinge, die mit der Rohrförderung von Feststoff-Fluid-Gemischen direkt zusammenhängen und das eigentliche Förderprinzip betreffen.

Principes du transport pneumatique et hydraulique par pipelines

Cet exposé donne une aperçu complet de la technologie de base et des principes de la conception sytèmes pneumatiques et hydrauliques destinés au transfert des mélanges solide-fluide.

Principios del transporte hidráulico y neumático por tuberias

Este artículo ofrece un examen completo de la tecnología básica y los principios importantes en el diséno de sistemas hidráulicos y neumáticos para el transporte de mezclas de sólidos-fluidos.

Summary

This paper gives a comprehensive overview of the basic technology and principles involved in the design of hydraulic and pneumatic systems for the conveying of solid-fluid mixtures.

1. Introduction

The principles for the calculation and the design of pneumatic and hydraulic conveying plants cannot be fully treated within the space available here. Only some essential points will be discussed which are related directly to the pipe flow of solid-fluid mixtures and which relate to the actual conveying principle. Besides this, the reader is referred to some basic texts of the special literature [1—10]. There, all those important problems are dealt with which concern the conveying systems as a whole, for example, economy of plants, plant components, treatment of the solids before and after transport, wear and plant operation.

In modern transport technology, the transportation in pipes seems to gain increasing interest despite some disadvantages which are inherent to the fluid mechanical principle. This fact is proven on the one hand by the fast increasing number of small and medium pneumatic and hydraulic con-

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Nomenclature

		definition	dimension
c_v	volume concentration in situ	V_s / V_{tot}	—
c_T	transport concentration by volume	$\dot V_s / \dot V_{tot}$	—
c_w	friction coefficient of a sphere		—
d	particle diameter		m
D	pipe diameter		m
Fr	Froude number (related to pipe)	v_f^2 / Dg	—
Fr_s	Froude number (related to solids)	w_{so}^2 / Dg	—
g	gravitational acceleration		m/s^2
H	vertical pipe length		m
$\dot M$	mass flow rate		kg/s
n	exponent in Durand's statement		—
p	pressure		N/m^2
Re	Reynolds number (related to pipe)	$v_f D / \nu_f$	—
Re_s	Reynolds number (related to solids)	$(v_f - v_s) \cdot d_s / \nu_f$	—
v	velocity		m/s
v'	variance of velocity		m/s
V	volume		m^3
$\dot V$	volume flow rate		m^3/s
W	drag		N
w_{so}	settling velocity of a single particle		m/s
λ	pipe friction coefficient		—
μ	mixing ratio	$\dot M_s / \dot M_f$	—
ν	kinematic viscosity		m^2/s
ϱ	density		kg/m^3

Subscripts

crit	critical at onset of deposition
f	fluid (gas or liquid)
h	horizontal
H	hoisting
ℓ	liquid
m	mixture
s	solid
tot	total
v	vertical
y	transverse to the main flow direction

veying plants (in-plant or interdepartmental) and on the other hand also by the increasing number of long cross-country pipe lines. Apparently, the advantages which are inherent to conveying plants using fluid mechanics are quite often outbalancing as a whole which results in economical conveying or production systems of which they are part of. The reader can judge by himself the advantages and disadvantages of conveying plants with pipes and their importance when looking at Table 1.

Table 1:
Advantages and disadvantages of hydraulic and pneumatic conveying

advantages	disadvantages
simplicity	relatively high energy consumption
adaptability	wear
little space required	attrition, degradation
easy selection of route	danger of pipe blocking
easy to branch off	relatively small flexibility
easy to control	suitability of solids for transportation is restricted
can be automated	eventually difficult treatment of solids before transportation
high degree of availability	eventually difficult dewatering
safe for the environment	eventually difficult dust separation
low inflation rate	
low maintenance costs	
can be integrated into processes therefore often good economy of operation	

By no means one should assume conveying systems using pipes would be generally more advantageous than other systems. It depends on the special case and its boundary conditions and it can be checked only by calculating the overall profitability. Quite often it is difficult to find a common base in order to compare competing conveying systems. It is still more difficult to obtain data for influences like political or economical reasons. There are, however, certain limits to this conveying principle which are given by physical facts and which must be kept in mind.

2. The Conveying Principle and its Variants

Conveying of solids by means of fluid mechanics means to carry and transport solids using the forces of a flowing carrier medium. These forces are the drag resistance and the pressure. Carrier medium can be a gas or liquid. Generally one must differentiate between pneumatic conveying and hydraulic conveying because the characteristics of these carrier fluids are totally different.

The drag resistance W of a solid particle in a fluid is proportional to the density of the fluid ϱ_f, the cross-sectional area of the solid particle and the square of the relative flow velocity, this means the difference between fluid velocity and solid velocity ($v_f - v_s$). The drag coefficient c_w is a factor of proportionality and is a function of the Reynolds number.

$$W = c_w(\mathrm{Re}_s) \cdot \frac{\varrho_f}{2} \cdot (v_f - v_s)^2 \cdot \frac{\pi \cdot d_s^2}{4} \tag{1}$$

The drag coefficient can be given with good approximation as follows:

$$c_w = \frac{24}{\mathrm{Re}_s} + \frac{4}{\sqrt{\mathrm{Re}_s}} + 0.40\,. \tag{2}$$

2.1 Hydraulic Conveying in Pipes

When using a liquid as carrier medium the conveying principle based on fluid mechanics can be used in a relatively advantageous manner. Since the density of these liquids is in the range of 1000 kg/m³, the solids which are to be conveyed experience already a buoyancy of $\varrho_f/\varrho_s \cdot 100\,\%$ — this amounts to about 40 % for sand in water. The suspended solids increase this buoyancy still more, amounting to $\varrho_m/\varrho_s \cdot 100\,\%$ in a mixture with an average density of ϱ_m. Due to this buoyancy and the magnitude of the fluid density a liquid can achieve the remaining required flow forces already at relatively small flow velocities. The energy input for hydraulic conveying can be small compared to pneumatic conveying. Besides this, the liquid is nearly incompressible and due to this fact very long conveying lengths are generally possible. Therefore, the hydraulic transportation can be very economical for very fine particles under certain conditions.

2.2 Pneumatic Conveying

When using gas as a carrier medium the conveying principle based on fluid mechanics is much affected by the low density in the range of 1 kg/m³. The buoyancy is more or less non-existent. These differences can be only equalized by increased velocities to obtain the required carrying force. The energy input for pneumatic conveying must be much larger compared to hydraulic conveying. Wear and attrition are also of greater importance. For these reasons, the velocity may not become too high. Gasses are, however, very compressible. The velocity is increasing along the conveying length due to the expansion which is caused by the pressure loss. Consequently, energy consumption and wear are increasing further. The enlargement of the pipe diameter step by step along the conveying length can decrease this detrimental influence of the compressibility and can slightly increase the achievable conveying length. Nevertheless, pneumatic conveying plants are resticted to about 3—4 km whereby the solids concentration must be also very small compared to hydraulic conveying. These reasons explain the use of pneumatic conveying plants being mainly interdepartmental (in-plant). Their importance is, however, often not recognised due to lack of publicity.

Table 2 illustrates the main aspects for a comparison between pneumatic and hydraulic conveyance in pipes.

If one is questioning under what conditions conveyance by fluid media is possible, the explanation for vertical conveying is easier than for horizontal conveying.

2.3 Vertical Conveying

In the case of vertical upward conveying the flow forces act as carrying and driving forces and are directed exactly opposite the weight of the solids. If the mean fluid velocity v_f is greater than the settling velocity of the solids w_{so} then the solids are hoisted with the velocity v_s .

Table 2:
Comparison between pneumatic and hydraulic conveying

	pneumatic conveying	hydraulic conveying
1. density of the carrier medium kg/m³	1.2—5	1000
2. required velocity m/s	≦30	≦5
3. weight reduction due to the buoyancy %	≈0	40 for sand
4. compressibility	very great	very small
5. specifications for the solids	dry fluid not too coarse	compatible with water fine for long distances eventually expensive preparation and dewatering coarse for short distances
if not qualified	capsule transportation	capsule transportation
6. possible conveying length as a result of 1, 2, 3, 4	≦ 4 km	unlimited for fine solids (the longer the more favourable) coarse solids ≦10 km
capsule transportation single stage	≦10 km	unlimited the longer the more favourable
7. specific energy consumption for a horizontal pipe kWh/tkm	1—10	0.1—1 vertical up to 10 and more
8. typical application	relatively short distances mostly interdepartmental chemical engineering combined with industrial processes bulk goods handling mining waste removal	short distances: interdepartmental, chemical engineering, combined with industrial processes, bulk goods handling, mining medium distances: mining, dredging, waste removal long distances: pipelines for coal, ore and other minerals, capsule transport

Since a profile of the fluid velocity exists and segregation must be avoided the following criterion must be well exceeded

$$v_f \gg w_{so} \quad (3)$$

Since already due to the required mass flow rate the flow in pipes is turbulent, the flow forces of the turbulent oscillations of the transverse velocities cause usually a uniform solids distribution over the cross-section. The settling velocity for single spherical particles is obtained from the above mentioned equilibrium of forces as

$$w_{so} = \sqrt{\frac{4}{3} \cdot \frac{d_s}{c_{w\,(Re_s)}} \cdot \frac{\varrho_s - \varrho_f}{\varrho_f}\, g} \quad (4)$$

when using Eq. (1) and (2). In practice, however, mostly non-spherical particles are present with non-uniform particle size distributions. Furthermore, the friction coefficient is subjected to more effects which makes it fairly impossible to calculate the settling velocity. In this case a test with suspended or settling particles can solve the problem.

2.4 Horizontal Conveying

It is more difficult to set up a conveying criterion for horizontal conveyance since the driving flow of the fluid runs horizontally. The gravitational force, however, acts vertically. The flow of the carrier must, therefore, produce driving forces and carrying transverse forces. In order to transport the solids in suspension, additional forces must be effective besides the buoyancy. The following effects might be active: Turbulent interchange in transverse direction, Magnus forces, assymmetrical flow around a body, assymmetrical impact at wall and at particles. Since these different effects superpose each other, it is not possible to set up, theoretically, a conveying criterion. Only for very fine particles, where only the buoyancy and the forces due to turbulence are effective, a similar conveying criterion as in the vertical case can be set up. For this purpose, the mean oscillation of the transverse velocity must be somewhat greater than the settling velocity if deposition is to be avoided:

$$\sqrt{\overline{v_y'^2}} \gg w_{so} \quad (5)$$

Since this oscillation of the transverse velocity averages about 5 % of the mean axial velocity this yields for the fluid velocity

$$v_f \gg 20\, w_{so} \quad (6)$$

In case that some transverse forces superpose each other, data obtained from experiments must be used. One must make sure that the conveying velocity is greater than the critical velocity at which the solids start to settle.

$$v_f > v_{crit} \quad (7)$$

It can be seen from Eq. (4) and (6) that not only flow forces exert an influence but also solids density and particle size. The finer and lighter the solids are the easier the above criterion can be exceeded. The more the fluid velocity exceeds the critical velocity the more uniform the solids are distributed.

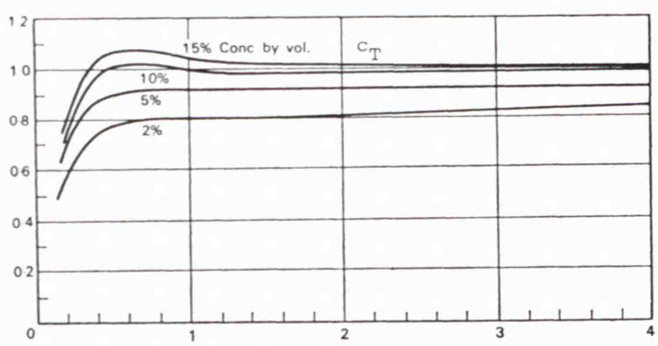

Fig. 1: Critical velocity for hydraulic conveying as a function of particle size, pipe diameter, density ratio and concentration according to Durand [1]

For hydraulic conveying the critical velocity can be read off Fig. 1, for pneumatic conveying from Fig. 2. Some characteristic flow conditions are forming depending on the above mentioned criterion and on some more important influential factors.

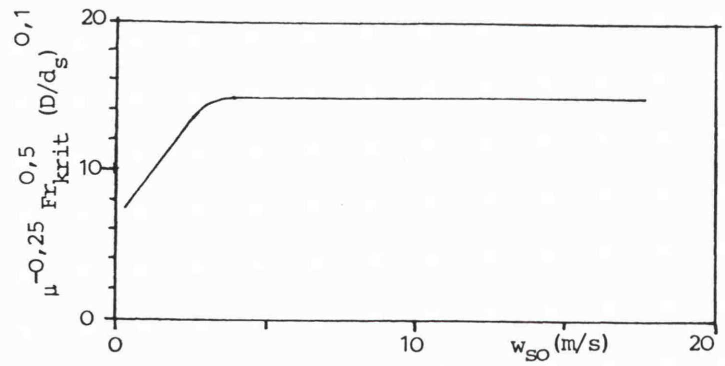

Fig.2: Critical Froude number for pneumatic conveying as a function of mixing ratio, settling velocity, particle size and pipe diameter from empirical data in the literature [2, 4, 5, 11, 13, 15]

3. Calculation of Hydraulic Conveying in Pipes

In hydraulic conveying one must differentiate between the three most important characteristic ranges which are discussed in the following.

3.1 Homogeneous Hydraulic Conveying

If the settling velocity of the solids is small enough (this occurs for sand, for particle sizes $d_s < 30\,\mu m$) that the slightest turbulence of the flow is sufficient to keep the solids uniformly distributed in suspension, then homogeneous conveying is given. Such a homogeneous suspension appears as a liquid having higher density and viscosity and can also be calculated analogous to the flow of pure liquids. In a generally valid way, the range of homogeneous conveying can be given with a Reynolds number related to solids for any solid:

$Re_s < 0.02$ homogeneous Newtonian flow*

* At high concentrations non-Newtonian behaviour can occur. More about rheology and classification in references [6, 7, 9, 15].

When using the mean density of the mixture

$$\varrho_m = c_v\,\varrho_s + (1 - c_v)\,\varrho_f \tag{8}$$

the head loss for a horizontal and a vertical pipe can be calculated as follows:

$$\frac{\Delta p}{L} = \left(\frac{\Delta p}{L}\right)_{fh,v} \cdot \frac{\varrho_m}{\varrho_f} \tag{9}$$

where the horizontal pressure gradient of the clear liquid is given as

$$\left(\frac{\Delta p}{L}\right)_{fh} = \lambda(Re)\,\frac{\varrho_f}{2}\,\frac{v_m^2}{D} \tag{10}$$

and the vertical pressure loss of the clear liquid as

$$\left(\frac{\Delta p}{L}\right)_{fv} = \lambda(Re)\,\frac{\varrho_f}{2}\,\frac{v_m^2}{D} \pm g \cdot \varrho_f \tag{11}$$

The mean velocity of the mixture is called v_m:

$$v_m = \frac{\dot V_s + \dot V_f}{A} = c_v v_s + (1 - c_v)\,v_f \tag{12}$$

The velocities of fluid and solid are equal: $v_f = v_s = v_m$. The transport concentration and the in situ concentration are also equal: $c_T = c_v$.

The friction coefficient for hydraulically smooth pipes can be used according to Blasius:

$$\lambda_f = 0.316\,\sqrt[4]{\frac{1}{Re}} \tag{13}$$

3.2 Pseudo-homogeneous Hydraulic Conveying

If a high degree of turbulence of the flow is required to keep the solids in suspension then the distribution of concentration in the horizontal pipe depends not only on the settling velocity of the solids but also on the transport velocity and on the pipe diameter. The solids are not distributed fully homogeneous any more. Usually this range is defined by $0.1 < Re_s < 2$ [15].

Table 3 shows conveying parameters at the lower and the upper range boundary for pseudo-homogeneous conveyance. For different solids density the particle sizes, settling

Table 3:
Boundaries for the pseudo-homogeneous conveying range according to [15]

$Re_s = 2$ $\quad w_{so}/v_m = 0.0056$

ϱ_s/ϱ_ℓ	—	1.5	2	2.5	3	4	5	6	7	8
d_s	μm	231	184	162	147	128	116	108	101	96
w_{so}	cm/s	0.97	1.25	1.42	1.56	1.8	1.98	2.12	2.26	2.38
v_ℓ	m/s	1.73	2.23	2.53	2.78	3.21	3.53	3.78	4.03	4.25

$Re_s = 0.1$ $\quad w_{so}/v_m = 0.0146$

d_s	μm	80	63	55	49,5	43,5	39,5	36,5	34,5	33
w_{so}	cm/s	0.147	0.186	0.214	0.236	0.27	0.298	0.322	0.34	0.36
v_ℓ	m/s	1.00	1.27	1.46	1.62	1.85	2.04	2.20	2.33	2.47

velocities and transport velocities are set up at a constant concentration profile. The solids distribution is nearly homogeneous at the lower boundary and is already slightly segregated at the upper boundary.

The calculation of pseudo-homogeneous mixtures can be carried out according to the equations which are valid for homogeneous mixtures.

3.3 Heterogeneous Hydraulic Conveying

At Reynolds numbers $Re_s > 2$ solids can be conveyed only as heterogeneous suspensions. The velocities of solid and fluid differ by the so-called slip. Only in the case of vertical conveying pseudo-homogeneous conditions regarding the solids distributions are existing due to the special force situation.

Therefore, the vertical case can be calculated with good approximation by applying the corresponding equations for homogeneous conveying.

For the horizontal case, the relationship set up by Durand has proven to be correct. It is presented here in a more generally valid way.

$$\frac{\frac{\Delta p}{L} - \left(\frac{\Delta p}{L}\right)_{fh}}{\left(\frac{\Delta p}{L}\right)_{fh} c_T} = K \left(\frac{g D}{v_m^2} \cdot \frac{\varrho_s - \varrho_f}{\varrho_f \sqrt{c_w}} \right)^n \quad (14)$$

When using $K = 83$ and $n = 1.5$ (corresponding to Durand's measurements with uniform sand) good results can be expected for nearly uniform solids. In case the solids show a wide particle size distribution the values for K and n can be completely different (compare Kazanskij [10]).

4. Calculation of Pneumatic Conveying

Also in pneumatic conveying different flow conditions can be expected. This depends on the ratio of conveying velocity to settling velocity and on the mixing ratio solids/gas.

4.1 Dilute Phase Conveying

At gas velocities $v_f \gg w_{so}$ and mixing ratios

$$\mu = \frac{\dot{M}_s}{\dot{M}_f} \quad (15)$$

of $\mu < 30$ conveyance in the dilute mode will occur when the distribution of solids is relatively homogeneous. In this conveying range the energy consumption is high but there is no danger of blocking. Besides this a maximum of conveying length is possible when the pipe diameter is increased step by step. Then the velocity varies between maximum allowable values and the critical velocity.

With decreasing velocity the conveying conditions are more economical but the solids distribution becomes heterogeneous. When reaching the settling velocity conveying occurs in the form of dunes or moving beds until at the critical velocity deposits occur eventually. Deposition happens in the region of the minimum of the pressure loss where transformation occurs from dilute phase to dense phase conveying. Dense phase, however, leads mostly to instationary conveyance as plugs.

4.2 Medium Phase Conveying

In the range of the critical velocity at mixing ratios $\mu > 30$ conveyance occurs with moving beds and dunes accompanied by more or less segregation. This type favours low energy consumption but does not exclude the danger of blocking.

4.3 Dense Phase Conveying

At high and at maximum mixing ratios $\mu \gg 30$ conveyance occurs as plugs for coarse material with high pressure gradients but low velocities. The specific energy consumption can become very low especially if fine solids are conveyed which can be fluidised. Due to the high pressure gradient of dense phase conveying the effect of the compressibility can be noticed already after a relatively short distance and causes these favourable conveying conditions to be left.

Most of these conveying conditions, especially dilute phase conveying, can be calculated by a statement which is set up analogous to the pressure loss of the clear fluid [2]

$$\Delta p = (\lambda_f + \mu \lambda_s) \frac{L}{D} \cdot \frac{\varrho_f}{2} v_f^2 \quad (16)$$

Here λ_s means the pressure loss coefficient of the solids which comprises the influences due to friction and weight. Its value must be determined empirically and is valid only for one specific type of solid. This coefficient is a function of a few essential influential factors.

Stegmaier [14] determined a mean value for this coefficient by correlating the data from a number of fine solids with the mechanics of similitude. This correlation yields (compare Fig. 3):

$$\lambda_s = 2.1 \cdot \mu^{-0.3} \cdot Fr^{-1} \cdot Fr_s^{+0.25} \cdot (d_s/D)^{-0.1}, \quad (17)$$

This correlation can also be performed for a single type of solid only to obtain greater accuracy. In this manner, the individual treatment of coarse solids is also possible.

The friction coefficient for the gas λ_f can be obtained again according to Blasius, Eq. (13), or it can be taken for actual cases from the well-known Nikuradse-diagram corresponding to a mean roughness of the pipe.

4.4 Vertical Pneumatic Conveying

Vertical pneumatic conveyance should be calculated with a special correlation corresponding to the way which is shown above for horizontal conveyance. If empirical data are lacking the horizontal correlation can be applied with good approximation if the hoisting of the solids in the pressure loss

$$\Delta p_{sH} = \mu \, \varrho_f \, g H \, \frac{v_f}{v_s} \quad (18)$$

is taken into account additionally. The influence of the weight of the gas can be neglected in general. In the literature, special correlations can be found for vertical conveying [7, 16].

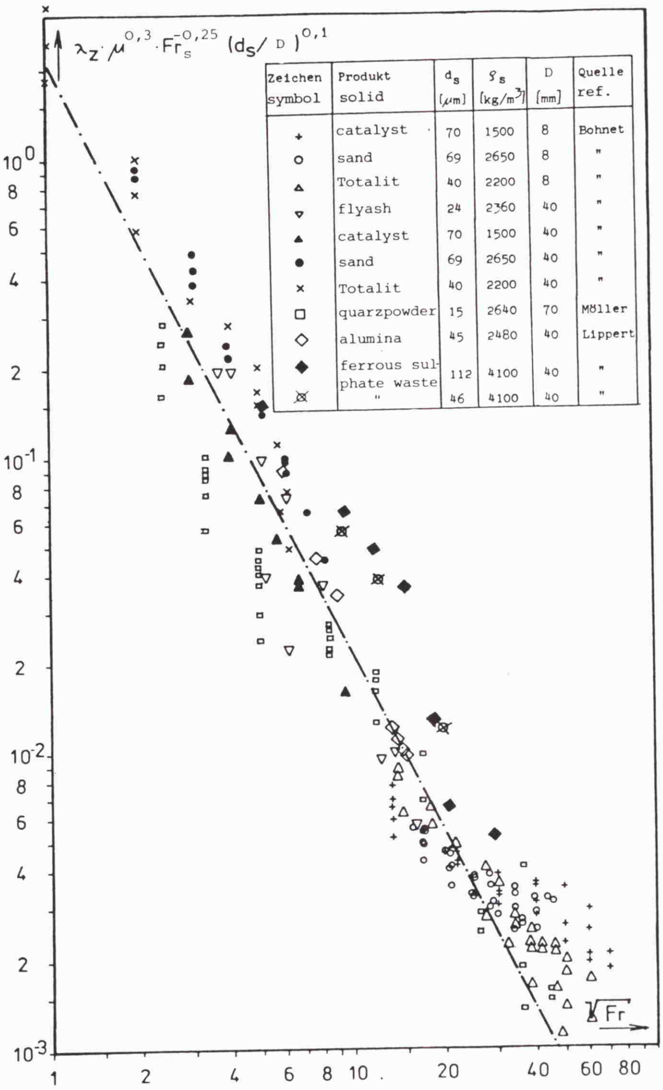

Fig. 3: Pressure loss coefficient for fine particles according to Stegmaier [14]

4.5 Influence of Compressibility

In case of a greater pressure loss, the expansion of the gas can be noticed along the pipe, which leads to an increasing velocity. For the calculation, this effect can be taken into account by correcting step by step the density according to the gas equation and the velocity according to the continuity equation (compare [8]).

If the gas velocity increases too much the energy consumption or the wear of plant components or the attrition becomes excessive and then the pipe diameter must be increased. This increase of diameter should be selected in such a way that the velocity does not fall below the critical velocity. For this calculation, the law of continuity, the new diameter and the local gas density must be taken into account. This means that a local Froude number multiplied by the density may not fall below the critical Froude number multiplied by the density:

$$\varrho_f \cdot Fr_{crit} = \varrho_f \frac{v^2_{fcrit}}{D \cdot g}$$

5. About the Problems of Basic Research

Despite the complexity of the conveying process using fluid forces the process must be described mathematically, if possible. The basic research work in the field of multiphase flow is, however, depending especially on experiments. The strict application of the similitude between model and prototype is not possible, which is an additional aggravating factor. The variance of measured results is correspondingly high if one tries to incorporate a greater range of the essential influential factors. Still more difficulties arise if one tries to comprise measured data of different origin.

The calculation in advance and the design of conveying plants is, therefore, subject to many uncertainties so that often expensive experiments are carried out using pilot plants.

In the fluid mechanics division of the author basic research work is done in the field of pneumatic and hydraulic conveying. This research aims on the one hand to improve, on a long-term basis the fundamentals for the calculation, on the other hand to set up very individual bases for calculations for special applications.

Part of the long-term efforts is the development of special measuring techniques and experimental methods which shorten the necessary times for experiments although they improve the quality of the data. By these means, an essentially reduced variance of the results can be obtained combined with a refined value of the measured data. Two of the applied measuring techniques are especially worth mentioning: The radiometric measurement of density profiles and the radiometric cross-correlation measurement, which allow to determine concentration profiles and profiles of the solids velocity (Fig. 4).

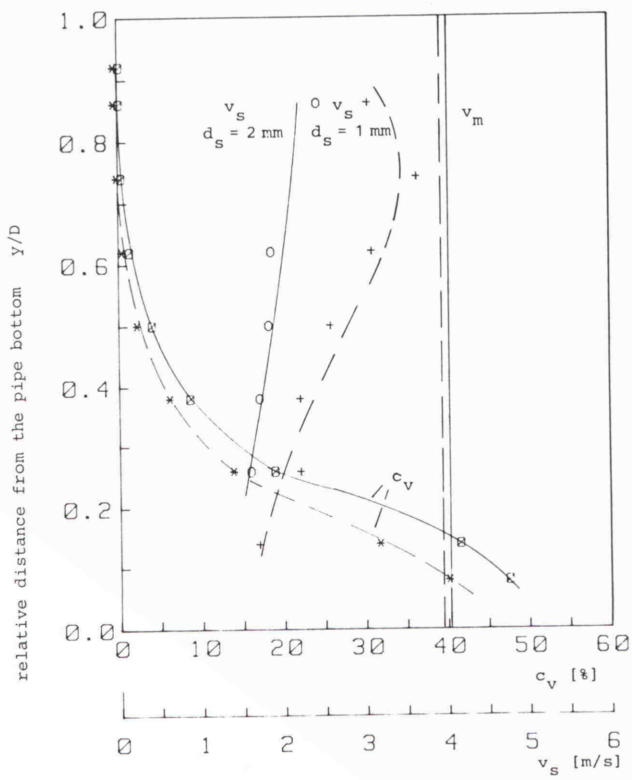

Fig. 4: Profile of the concentration and of the solids velocity and the mixture velocity for two uniform distributions of steel spheres for horizontal hydraulic conveying (diameter 80 mm)

A modern digital online system for data acquisition and data analysis ensures relatively short times for experiments despite sophisticated measuring techniques. All test rigs can be connected to this data acquisition system.

This technology for measurement and experiment is applied for basic investigations leading to correlations which are more generally valid and which are half-empirical. For example, at the moment the influence of the particle size distribution is investigated using glass and steel balls. This influence is one of the main reasons for great variances between calculated and measured pressure losses (compare [17]).

For a further improvement of the calculation bases, theoretical considerations aim at increasing the weighting of the actual motions in a multiphase flow in the mathematical statements (compare [18]).

These long-term efforts to improve the bases of calculations are completed by the individual set-up of calculations and designs for special applications. These individual calculations comprise the test results for the special case as well as the results of the general research work.

Since these special calculations are carried out in each case for one type of solid only the achievable accuracy of the calculation is much greater.

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