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ACCELERATION OF CORK STOPPERS IN PNEUMATIC CONVEYING

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Abstract. *In the cork stoppers industry short distance pneumatic conveying is commonly used in several phases of the manufacturing process. Systems have been developed purely on an empirical basis and until two years ago no systematic approach to the study of this problem had been undertaken. Since then, some experimental work was carried out mainly on steady state horizontal pneumatic conveying of cork stoppers and shed some light on the pressure drop evolution in this process. However, transportation distances usually found in the pneumatic conveying of cork stoppers are short and industrial applications are essentially under unsteady-state conveying regimes. The present paper reports an experimental study of the acceleration regime for horizontal conveying conditions presenting data on the pressure drop evolution and acceleration length for two stoppers sizes and several loading conditions. Correlations for the pressure drop and acceleration length are presented as function of solids load factor, gas and solid density ratio, particle and duct size ratio and Froud number.*

Keywords: Pneumatic conveying, Gas-solid flow, Acceleration regime.

1. INTRODUCTION

Since the last forties the technical literature on pneumatic conveying suffered a strong interest and a qualitative approach to the comprehension of two phase flow regimes was presented by Zenz (1949) and afterwards many simple empirical correlations were presented by several authors for the design of conveying systems, Fisher (1958), Bannister (1959a, 1959b) and Orr (1966). There was then an evolution of the developed models for the calculation of the steady state pressure drop in pneumatic conveying systems following a general approach involving the separate calculation of individual contributions, the transporting air pressure drop and the transported solids pressure drop. One classical model was developed by Barth (1960a, 1960b, 1963). This model is dependent upon an experimental impaction factor, λ_p, for which experimental data in the international technical literature is scarce. Many researchers have been working around the fundamental concepts of this model as Rizk (1976, 1986), Szikszay (1988) and Weber (1991). Using the same approach for separate calculations of gas and solids pressure drop, but not making any distinctions between gravity effects and inter-particles or particles-confining walls impaction effects, Yang and co-workers developed a model with a simpler utilisation procedure, Yang (1973, 1974, 1978) and Yang and Keairns (1973, 1976). Both models assume the increase of the overall pressure drop when moving from pure air flow towards gas-solid flow. However, in some well documented situations, like those studied by Szikszay (1988), it was found a pressure drop reduction when changing from pure gas to gas-solid flow. This same trend was found by Radin *et al.* (1975) working with non-Newtonian fluid flows and Weber (1991), who proposed another model to account for the different behaviour of the air flow under the influence of conveyed solid particles.

In the pneumatic conveying of cork stoppers the fine cork dust that is released during the conveying process acts as a lubricant, reducing friction effects, Neto and Pinho (1998), an effect that can be enhanced by electrostatic generation, Smeltzer *et al.* (1982). As a practical result it has been found a decreasing of the pressure drop with the increase of the solids mass loading and thus, the standard procedure for the pressure drop calculation could not be used. A correlation for the total pressure drop (air plus solid) on pneumatic conveying of cork stoppers was then developed, Neto and Pinho (1998), using an overall friction factor. However these results are of limited practical application; industrial conveying of cork stoppers is essentially a short distance process due to the extreme fragility of cork stoppers and in many real situations the stoppers conveying occurs essentially under accelerating conditions. The study of acceleration regimes in pneumatic conveying is rather limited Klinzing (1981), and not many empirical data and subsequent pressure drop and acceleration length correlations are available for design purposes, Rizk (1986). Usually, the weight of the acceleration regime pressure drop can be of small importance in the overall assessment and this explains the reduced information available. Exceptions are the Rose and Duckworth's equations for pressure loss in acceleration and for the acceleration length, as referred into Klinzing (1981).

2. EXPERIMENTAL APPARATUS AND PROCEDURE

For the experimental procedure cork stoppers of two different sizes, length $\times$ diameter, were used, Table 1. The equivalent particle diameter, d_p, is defined as the diameter of the sphere with the same volume times the cork particle sphericity, ϕ.

Table 1. Overall characteristics of tested cork stoppers

	Size ($l \times d$) (mm×mm)	d_p (m)	ϕ	ρ_p (kg/m^3)
1st Type	45×24	0.0283	0.839	178.9
2nd Type	38×22	0.0256	0.847	178.9

The experimental system as schematically depicted in Fig 1, was composed by a 14 m long horizontal PVC, 125 mm nominal diameter pipe (122 mm internal diameter, D), where pressure drop measurements were taken, and the recovery circuit composed by two 90º bends and another 14 m long straight. Cork stoppers, moving in a closed circuit, were introduced into the pneumatic conveying circuit through a feeding hopper that received also the corks after their tour into the system. Conveying air was introduced into the system through a centrifugal fan controlled by a frequency variator with a resolution of 1 Hz/50 Hz. Air flow was measured through an orifice plate flow meter positioned upstream the feeding hopper, and equipped with a differential pressure transducer with an operating range of 0 to 1245 Pa. The orifice plate flow meter was previously calibrated by means of a Pitot tube installed at the final discharging point of the circuit. Using the Pitot, tube an average conveying air velocity was obtained through the log-linear method and the measurement of the air velocity in six points along the pipe diameter. Corrections for air leakage through the corks feeding system were taken into account, by comparing pressure drop versus air velocity curves with and without the feeding system installed on the circuit. Comparisons were only made in the absence of pneumatic conveying and uncertainties inherent to the corks entrance into the conveying pipe could not be accounted for. With the continuous reading of conveying air temperature along the test region, corrections in the air flow rate were made for the air temperature increase with attrition effects inside the transporting pipe. In summer conditions, average conveying air temperature could be up to 10 ºC above the orifice plate reference temperature of 20 ºC.

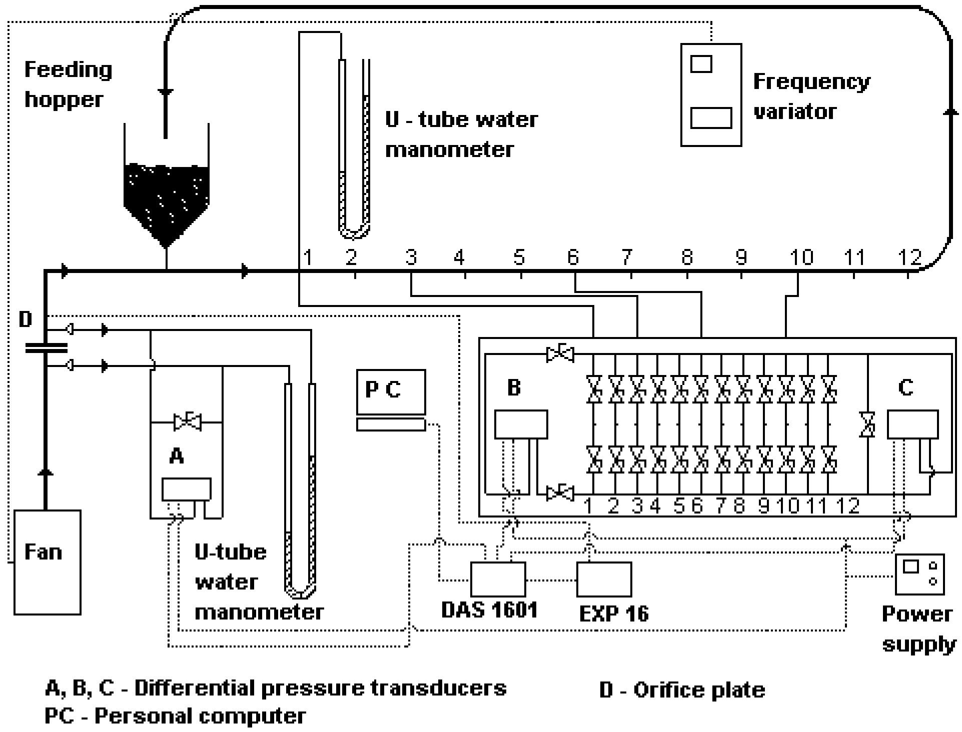

Figure 1 - Schematic diagram of the experimental apparatus.

Along the low horizontal pipe pressure taps were fitted one meter apart. The first pressure tap is 2 m away from the feeding hopper. For the pressure drop measurements, along the conveying pipe, a differential pressure transducer in the 0-490 Pa range was used. This device had an output signal of 0-1 V dc. A data acquisition system (DAS 1601 plus EXP 16 boards) installed on a personal computer received information from the two differential pressure transducers on use (one for the orifice plate pressure drop and the other conveying pressure drop), as well as temperature readings of the conveying air through three type t thermocouples. The accuracy of differential pressure drop measurements considering also the data acquisition process was of 9.7 Pa for the 0-1245 Pa pressure transducer and of 7.9 Pa for the 0-490 Pa pressure transducer.

For each testing situation characterised by a definite air flow rate and solids loading factor θ (ratio between the solids mass flow rate and the conveying air mass flow rate), pressure drop measurements were made throughout the straight horizontal lower transporting pipe. Data were sequentially taken between the first and subsequent pressure taps. In the first two meters of the conveying line pressure measurements were not taken, as close to the stoppers entrance flow instabilities rendered pressure data erratic and thus difficult to interpret. The adopted option was then to work downwards from the first pressure tap to find out the length of the acceleration zone, assuming that the pressure drop trend line could be extrapolated upwards till the feeding point.

To calculate the mass flow rate of transported cork stoppers a basket was used as particles collection device. The collected batch of particles, for a definite time interval, was weighted and solids mass flow rate could then be calculated. The measurement of the voidage fraction during pneumatic conveying was carried out through the knowledge of the amount of cork stoppers that in a given instant remain inside the pipe. Having the experimental installation working in steady state conditions, the feeding hopper was suddenly stopped and all the cork stoppers being conveyed were immediately collected and weighted. This was, for the stoppage instant, the amount of particles remaining inside the conveying system. Comparisons between the overall corks volume and the inside volume of conveying pipe gave the voidage fraction under normal conveying conditions.

3. EXPERIMENTAL RESULTS

The first observation of experimental results was to find out the acceleration length, L_a, region for the tested stoppers sizes. The pressure drop even in an acceleration regime can, for practical purposes, be defined in terms of fully developed flow parameters like the gas density, ρ_f and interstitial velocity, U_f,

$$\Delta p_a = \lambda_a \rho_f \frac{L_a}{D} \frac{U_f^2}{2} \tag{1}$$

where the acceleration friction factor is to be considered, analogously to the steady state regime, see Szikszay (1988), Weber (1991) and Neto and Pinho (1998), a function of the solids load factor θ, air flow Froude number $Fr = U_f \big/ \sqrt{g\ D}$, particles density ρ_p, and equivalent diameter d_p, and transporting air density ρ_f,

$$\lambda_a = \alpha\ \theta^{\beta}\ Fr^{\gamma} \left(\frac{d_p}{D}\right)^{\delta} \left(\frac{\rho_p}{\rho_f}\right)^{\nu} \tag{2}$$

where α, β, γ, δ and ν are fitting parameters to be determined from experimental results. However, before going to this phase it must be found out what is the range of pressure drop results belonging to the acceleration regime. For that determination and according to Eq. (1), experimental data were treated in the form of a dimensionless pressure drop, $P^* = \Delta p \Big/ \left(\rho_f \frac{L}{D} \frac{U_f^2}{2}\right)$, and plotted, in Fig. 2, as a function of the distance between correspondent pressure taps. Figure 2 is very clear, the dimensionless pressure drop decreases rapidly with covered distance and beyond pressure tap number five, equivalent to a covered length of three to four meters, the acceleration process is accomplished. Accordingly, for the determination of the fitting parameters correspondent to the acceleration average friction factor, λ_a, only data taken between pressure taps 1-2, 1-3, 1-4 and 1-5 were considered. For each cork particle size, differences in the pressure drop, easily seen in Figure 2, are functions of the used loading factor.

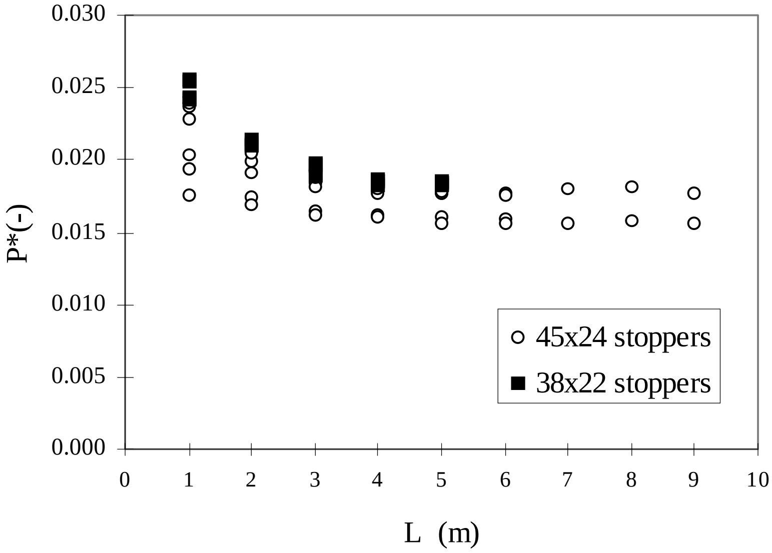

Figure 2 - Evolution of total pressure drop in the acceleration region.

The resultant correlation for the acceleration friction factor is

$$\lambda_a = 7.601\times10^{-6}\ \theta^{\ 0.1005}\ Fr^{\ -0.3851}\left(\frac{d_p}{D}\right)^{-0.3183}\left(\frac{\rho_p}{\rho_f}\right)^{1.742} \tag{3}$$

The accuracy of this correlation is expressed as the mean deviation in percent, calculated through the comparison between experimental and calculated values for $P*$,

$$\text{Mean Deviation, }\% = \left[\sqrt{\sum\left(\frac{P*\ cal - P*\ \exp}{P*\ \exp}\right)^2 \Big/ N}\right]\times100 \tag{4}$$

as defined by Wen and Chen (1982) and is 9.69 % while the maximum absolute deviation is 17.1 %.

The equation for the calculation of the pressure drop during the acceleration regime is then Eq. (1) using λ_a as defined by Eq. (3). However, the application of Eqs. (1) and (3) for the calculation of acceleration pressure drop can only be useful if the acceleration length is known. With the experimental set-up employed in the present work rigorous determination of the acceleration length was hindered because distance between pressure taps was too large to give a good accuracy. However, consulting Fig. 2 an overall idea of the order of magnitude of acceleration lengths involved in the experimental setup can be obtained (3 to 4 m), and used as reference to compare with the results obtained from a simple equation of acceleration length to be derived next.

4. ACCELERATION LENGTH AND PRESSURE DROP

Inside a volume element of conveying pipe with a cross section surface area A and elemental length dL there is an elemental mass of cork stoppers, dm_p, flowing at the velocity U_p, which is suffering an acceleration process. To accelerate this mass element of cork stoppers an elemental force dF_{ta} is required,

$$dm_p \frac{dU_p}{dt} = dF_a \tag{5}$$

where,

$$dF_a = dp_a \, A \; \varepsilon \tag{6}$$

with,

$$dp_a = \lambda_a \rho_f \frac{U_f^2}{2} \frac{dL}{D} \tag{7}$$

On the other end, $dm_p = (1-\varepsilon)\rho_p A \; dL$, where ε is the average voidage fraction in the conveying system, and then the elemental force required for the acceleration is

$$dF_a = \lambda_a \rho_f \frac{U_f^2}{2} \frac{\varepsilon}{D} \frac{dm_p}{(1-\varepsilon)\rho_p} \tag{8}$$

Replacing this equation into Eq. (5)

$$\frac{dU_p}{dt} = \lambda_a \frac{\rho_f}{\rho_p} \frac{U_f^2}{2\;D} \frac{\varepsilon}{(1-\varepsilon)} \tag{9}$$

but, as previously assumed in the Eq. (2)

$$\frac{dU_p}{dt} = \alpha \; \theta^{\beta} \; Fr^{\gamma} \left(\frac{d_p}{D}\right)^{\delta} \left(\frac{\rho_f}{\rho_p}\right)^{\nu-1} \frac{U_f^2}{2\;D} \frac{\varepsilon}{(1-\varepsilon)} \tag{10}$$

where the first member can be written as $\frac{dU_p}{dt} = \frac{dU_p}{dL}\frac{dL}{dt} = \frac{dU_p}{dL} U_f$ and finally, according to the definition of solids load factor, $\theta = \frac{1-\varepsilon}{\varepsilon}\frac{\rho_p}{\rho_f}\frac{U_p}{U_f}$, Eq. (10) takes the form,

$$\frac{dU_p}{dL} = \alpha \; \theta^{(\beta-\gamma-1)} \left(\frac{1}{\sqrt{g\;D}}\right)^{\gamma} \left(\frac{d_p}{D}\right)^{\delta} \left(\frac{\rho_p}{\rho_f}\right)^{\gamma+\nu} \frac{1}{2\;D} \left(\frac{\varepsilon}{1-\varepsilon}\right)^{-\gamma} U_p^{\gamma+1} \tag{11}$$

which can be integrated between L = 0 and U_p =0 and L=L_a and U_p=U_p. The resultant equation after replacing the particle velocity using again the load factor definition is

$$\frac{L_a}{D} = \frac{2}{-\gamma\alpha}\theta^{(1-\beta)}\,Fr^{-\gamma}\left(\frac{d_p}{D}\right)^{-\delta}\left(\frac{\rho_f}{\rho_p}\right)^{-\nu} \tag{12}$$

and substituting the fitting factors obtained beforehand for the acceleration pressure drop, a correlation is obtained

$$\frac{L_a}{D} = 6.833\times10^{5}\,\theta^{0.8995}\,Fr^{0.3851}\left(\frac{d_p}{D}\right)^{0.3183}\left(\frac{\rho_f}{\rho_p}\right)^{1.742} \tag{13}$$

For the calculation of the acceleration pressure drop a simple equation can then be derived. Replacing λ_a from Eq. (2) and L_a/D from Eq. (12) into Eq. (1) the following results,

$$\Delta p_a = \frac{2}{-\gamma}\,\theta\,\rho_f\,\frac{U_f^{\,2}}{2} \tag{14}$$

which, in the present situation case gives, in S.I. units,

$$\Delta p_a = 5.194\,\theta\,\rho_f\,\frac{U_f^{\,2}}{2} \tag{15}$$

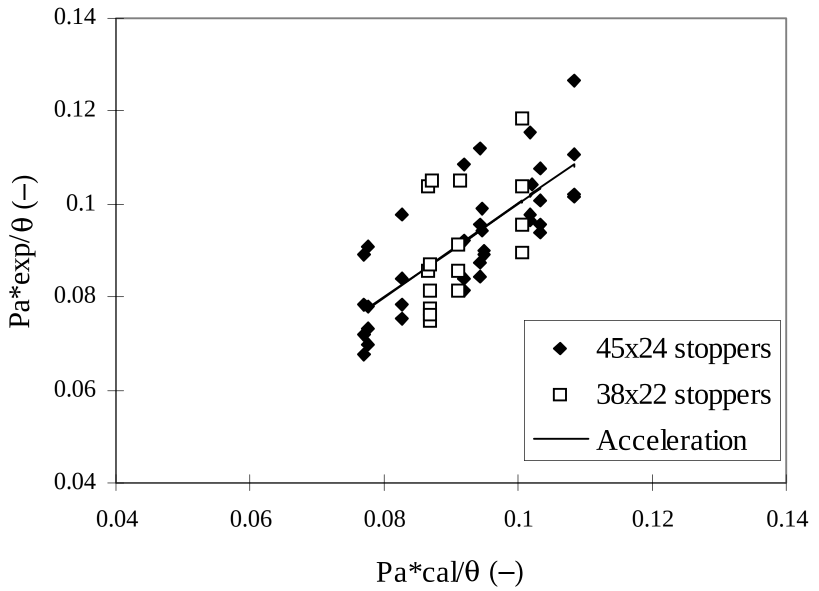

Figure 3 - Comparison between calculated specific acceleration pressure drop and experimental values obtained in parts of the acceleration region.

It is now important to evaluate the accuracy of the above correlation compared with experimental data. Although total acceleration pressure drop measurements were not taken, measurements obtained during several parts of the acceleration interval can be used to assess the accuracy of (15), through the plot of experimental dimensionless pressure drop data, P_a^*/θ for pressure probes 1-2, 1-3, 1-4 and 1-5, against P_a^*/θ , calculated with Eq. (15). Once again the average deviation between experimental and calculated specific pressure drop is 9.69 % and the maximum absolute deviation is 17.1 %, Fig. 3.

Experimental data points above the line of the total specific acceleration pressure drop are correspondent to measured values, early in the acceleration process, obtained from pressure taps 1-2. Such early acceleration results have, as can be seen from Fig. 2, higher specific pressure drop. In both Figs., 2 and 3, each data point is in fact an average of at least a minimum of ten experimental values. Acceleration lengths calculated through (13) are well inside the tendency shown in Fig. 2, and have values ranging from 3.5 to 4.9 m covering gas interstitial velocities from 19 to 27 m/s and solids load factors from 0.10 to 0.16.

5. CONCLUSIONS

An experimental work was carried out to study the acceleration regime of cork stoppers in dilute phase horizontal pneumatic conveying. For the pneumatic conveying of cork stoppers solid and gas phase effects cannot be conveniently separated because of the lubricating action of the fine cork dust released during transportation. This situation happens either in steady state or in transient conveying conditions and the correct approach to the pressure drop evaluation is to consider only overall values.

From pressure drop experimental data during the acceleration process an empirical correlation for the acceleration friction factor was obtained and afterwards through a very simple theoretical approach a correlation for the acceleration length was developed. Finally combining the friction factor correlation with the acceleration pressure drop length an equation for the acceleration pressure drop was found.

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