ACCELERATION LENGTHS IN VERTICAL PNEUMATIC CONVEYING OF CORK STOPPERS

Ricardo Barbosa
Department of Mechanical Engineering and Industrial Management, ESTV, Polythecnic of Viseu, Viseu, Portugal
rbarbosa@demgi.estv.ipv.pt

Carlos Pinho
CEFT-DEMEGI, University of Oporto, Rua Dr.Roberto Frias, s/n
4200-485 Porto, Portugal
ctp@fe.up.pt

Abstract. *The pneumatic transportation of cork stoppers is used in the primary steps of the corks production process, when particle damage through impaction amongst them or against the confining walls has a minor effect upon their cylindrical shape.*
In the industry, short distance transportation systems are used and in such circumstances the particle acceleration regime plays a dominant role in the conveying process.
Some experimental studies have, in the past, been carried out in horizontal and vertical conveying. However, data for acceleration regime in the vertical conveying of cork stoppers are yet to be published.
In this paper experimental results for the acceleration lenght during vertical conveying of three cork stopper sizes are shown and a correlation is proposed as a function of the solids loading factor and other parameters characterizing this particular type of gas solid flow.

Keywords*: vertical pneumatic conveying, acceleration length, cork stoppers*

1. Introduction

Pneumatic conveying of cork stoppers has been used in some steps of the cork industry, where the basic approach for the design of the conveying systems is purely empirical, and the technical and scientific data on such matter is scarce. There were however some studies on the horizontal conveying of cork stoppers, Neto and Pinho (1998), Pinho (1999) and Pinho (2001). Afterwards, the work moved towards the study of steady state vertical conveying, Barbosa and Pinho (2004), while in the present paper results on the transient acceleration regime in vertical pneumatic transportation are presented and discussed.

In the horizontal pneumatic conveying of cork stoppers, fine cork dust is released and acts as a lubricant reducing friction effects, Neto and Pinho (1998). The deposition of this fine dust is still enhanced by electrostatic generation, Smeltzer *et al.* (1982). The conveying air pressure drop is then reduced, with the increase of the solids mass loading. This situation has already been found on solid-liquid systems; Lee *et al*. (1974) studied polymeric solutions containing suspended fibres and Radin *et al.* (1975) studied the drag reduction in several dilute solid-liquid suspensions. Szikszay (1988) argued that, as the measured experimental data referred to both the solids and the conveying air pressure drop, it was unreasonable to separate them. Weber (1991) also suggested that a single friction factor for the gas-solid mixture should be used, instead of two separate friction factors, for the air and solids flow. This question of drag reduction with the addition of particles into a flow stream has been recently reviewed by Fan and Zhu (1998), who presented a phenomenological model to account for the drag reduction.

Although drag reduction was detected in horizontal conveying of cork stoppers, in vertical pneumatic conveying the action of the gravity forces was such that the fines felt against the main gas flow and no preferential fines deposition occurred on the inner walls of the conveying pipe. Thus no drag reduction took place and in vertical pneumatic conveying, the overall gas plus solid pressure drop was higher than the corresponding value for the single gas flow, Barbosa and Pinho (2004). Classical theories like those of Barth (1960a, 1960 b) or of Yang (1973; 1974; 1975; 1978), could then be adapted to the vertical pneumatic conveying of cork stoppers. However, to follow the same approach used in the studies of horizontal pneumatic conveying of cork stoppers and to obtain comparable final correlations, a single friction factor for the gas solid mixture was adopted also for the vertical pneumatic conveying.

In vertical pneumatic conveying the important research points concern the acceleration region, the gas and solids friction factor (Rautiainen *et al.*, 1999) and the definition of flow choking conditions. Recent examples of studies on the characterization of the acceleration region are the publications of Dzido *et al*. (2002) and Namkung and Cho (2002), although the works of Yang and co-authors are still a basic reference (Yang and Keairns, 1976). Among the recommended correlations for the calculation of the friction factor are those of Yang (1973), Yang (1974) and Yang (1978). For the definition of the choking conditions, again the work of Yang (1975) is frequently recommended in many recent publications, like for example Raczek and Palica (1997) and Xu *et al.* (2001).

A previous paper of Barbosa and Pinho (2004) presented a correlation for the gas solid friction factor for steady state vertical pneumatic conveying of cork stoppers, while in the present paper the acceleration length of the cork stoppers, in the transient portion of the vertical conveying pipe, is accounted for.

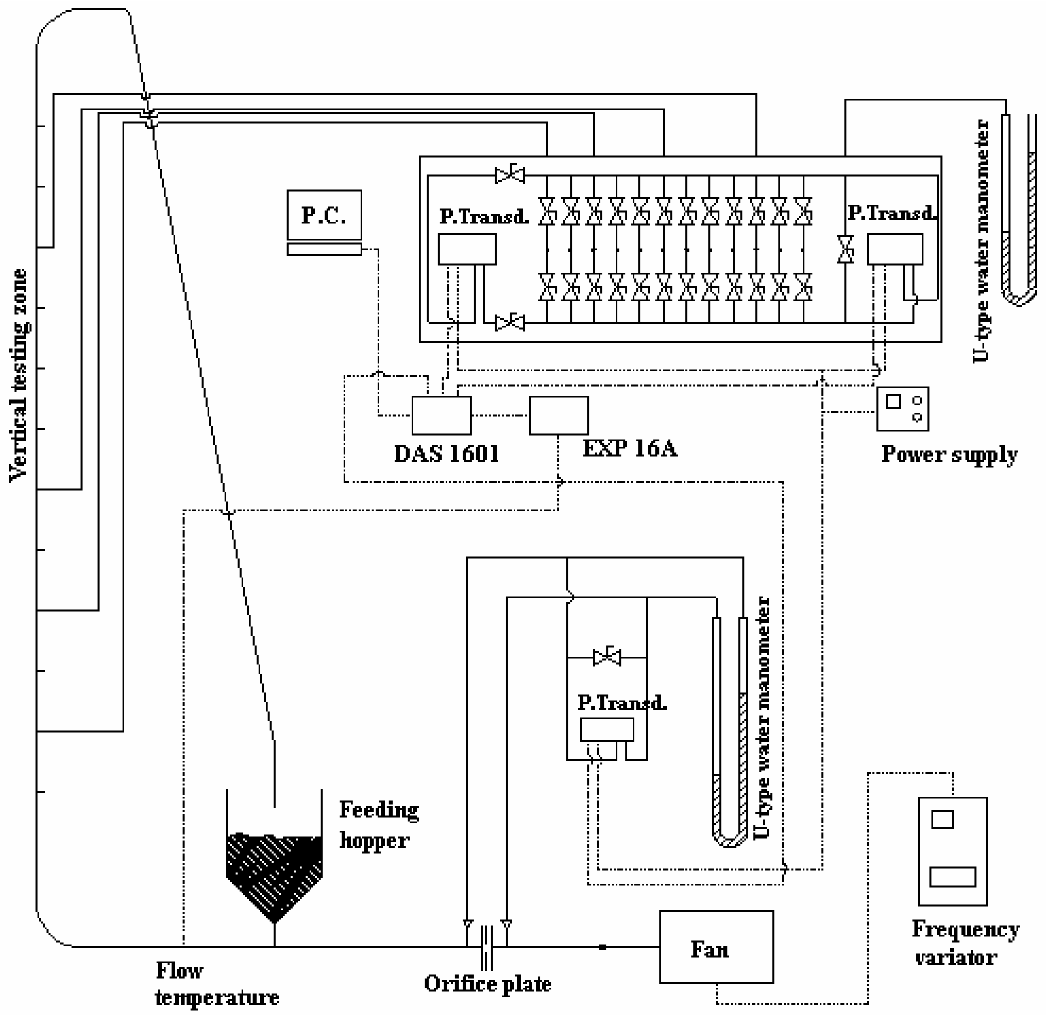

Figure 1. Schematic diagram of the experimental apparatus.

2. Experimental procedure

The experimental system is schematically shown in Fig 1, it was composed by a 6 m long horizontal portion where the stoppers were introduced into the conveying pipe, a vertical testing section of 6.8 m length and the recovery circuit composed by a small horizontal portion of 1.6 m and a diagonal portion 5.9 m long. The tube was a PVC pipe with 125 mm nominal diameter pipe (122 mm internal diameter, *D*). Cork stoppers, moving in closed circuit, were introduced into the pneumatic conveying system through the feeding hopper, installed in the horizontal portion of the duct, Fig. 2. Conveying air was introduced into the system through a centrifugal fan controlled by a ABB frequency variator model ACS401000932, with a resolution of 0.1 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 before the feeding hopper.

Detailed information on the calibration procedure for the orifice flow meter can be found in Barbosa and Pinho (2004).

Along the vertical testing section, pressure taps were fitted half a meter apart. The first pressure tap is 0.5 m away from the bend connecting the horizontal feeding section and the vertical testing section. For the pressure drop measurements along the conveying pipe, differential pressure transducers in the 0 to 490 Pa range were used. The transducers were from Series T of Modus Instruments, Inc., and had output signals of 0-1 V dc. The transducers outputs were checked towards U-type water manometer readings. A data acquisition system (DAS 1601 plus EXP 16 boards) installed on a personal computer received information from the differential pressure transducers on use (for the orifice plate pressure drop and the conveying pressure drop), as well as temperature readings of the conveying air through a type T thermocouple, Fig. 2. 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.

Figure 2. Images of the feeding hopper and of the data acquisition system.

For each tested situation characterized by a given 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 vertical transporting pipe, using all the available pressure taps. Through the adequate grouping of the pressure drop measurements, like for example the sequential combination between the first and subsequent pressure taps, it was possible to get an overall idea of the evolution of the pressure drop, as a function of particle entrance effects in the vertical portion of the pipe and also of the particle acceleration.

To calculate the mass flow rate of transported cork stoppers a basket was used as collection device for conveyed particles. The collected batch of particles, for a definite time interval, was weighted and the 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.

Table 1 presents some physical characteristics of the tested cork stoppers; l, d and ψ are respectively the length, diameter and sphericity of the stoppers, d_{eq} is the diameter of a sphere with identical volume and ρ_p is the density of the particles.

Table 1 – Characteristics of cork stoppers used in the experiments.

Size ($l \times d$) (mm×mm)	d_{eq} (m)	ψ	ρ_p (kg/m^3)
38 × 22	0.0302	0.85	167
38 × 24	0.0320	0.85	155
45 × 24	0.0339	0.84	139

3. Experimental results

The first step in the analysis of the experimental data was to define the initial acceleration region were the gas solid flow is under transient conditions and the final steady state conveying region. This was carried out by observing how the pressure drop per unit length of conveying pipe changed along it. This pressure drop per unit length has initially low values as corks are moving away from the curve separating the horizontal portion of the conveying pipe from the vertical one. In the first portion of the vertical pipe, particles are moving slowly and the velocity differential between the gas and the solid phase is high, increasing the drag effect upon the particles that start to be re-accelerated. However, this phenomenon is just starting and thus the overall pressure drop corresponding to the first measurement still indicates a lower value. Afterwards, the pressure drop rises up to a maximum around 1 or 2 meters away from the curve and then diminishes slowly until reaching an almost constant value beyond 3 to 3.5 m, where steady state conveying conditions predominate. Figure 3 presents, for some experimental runs, such evolution of the pressure drop.

The plot of pressure drop per unit length ($\Delta P / L$) as a function of several parameters, the solids loading factor θ and the Froude number of the flow ($Fr = U_f / \sqrt{g D}$), to characterize the operation of a pneumatic conveying system, is a typical procedure found in the technical literature (Marcus *et al.*, 1985; Marcus *et al.*, 1990; Rhodes, 1998; Rautiainen *et al.*, 1999). In the definition of the Froude number, U_f is the interstitial air velocity, D is the internal diameter of the conveying pipe and g is the acceleration of gravity.

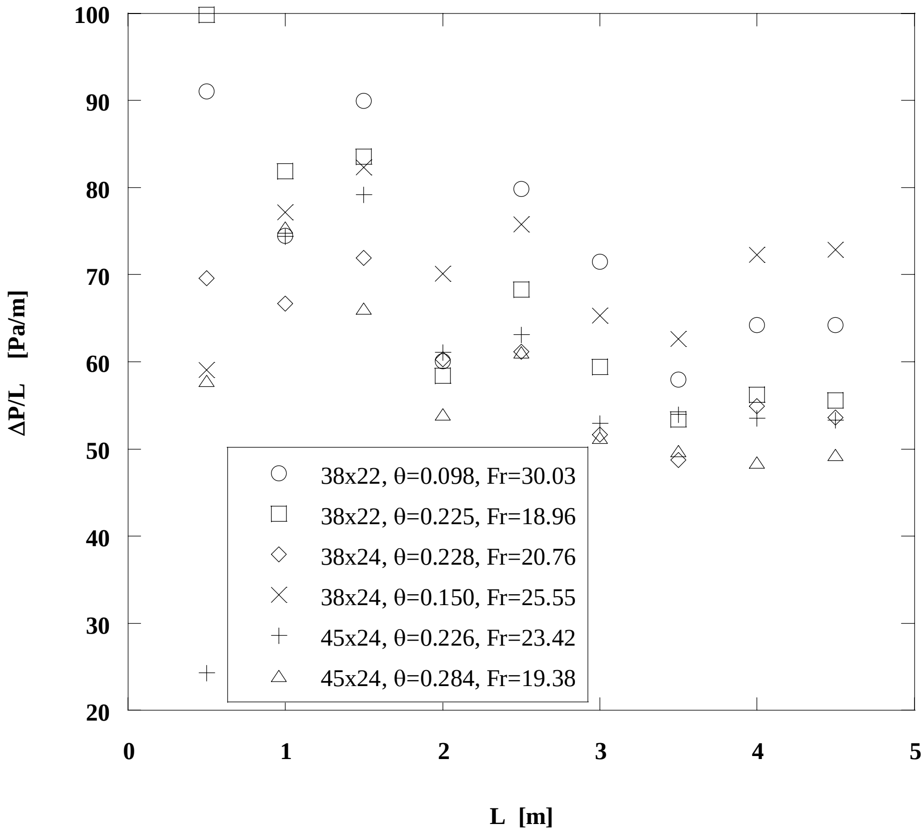

Figure 3. Typical evolution of overall pressure drop along the conveying pipe.

The order of magnitude of the length of the acceleration region (Barbosa and Pinho, 2004) is similar to what was found for horizontal pneumatic conveying of cork stoppers (Pinho, 1999; Pinho, 2001). On the other end, pressure drop data obtained with pressure taps close to the end of the vertical conveying pipe, i.e. beyond 4.5 m, were not plotted as the flow deceleration, in the approach to the curve connecting the vertical testing section with the final cork recovery portion of the rig, induces the increase of the pressure drop, and again unsteady conveying conditions were obtained.

The definition and characterization of the acceleration region in pneumatic conveying has been very limited and up to now no universal phenomenological theory has been developed to explain the phenomena taking place in this region of a conveying system. The approaches found in the literature are either semi-theoretical leading to some equations difficult to integrate in order to obtain an expression useful for calculation and design (Klinzing, 1981; Marcus *et al.*, 1985; Marcus *et al.*, 1990), or purely empirical leading to correlations strictly based on experimental results. This last approach is also used in the present discussion. However, to justify the form of the correlation to be used and explanation follows.

It is known that either for steady state conveying as well as for the transient acceleration portion of the conveying pipe, the overall gas plus solid pressure drop can in a simple way be quantified by an expression of the type (Szikszay, 1988, Weber, 1991; Neto and Pinho, 1998; Pinho, 1999; Pinho, 2001, Barbosa and Pinho, 2004),

$$\Delta p_t = \lambda_t \frac{L}{D} \rho_f \frac{U_f^{\,2}}{2} \qquad (1)$$

both for horizontal or vertical transportation processes and where the global friction factor λ_t, is written as a simple function of dimensionless parameters,

$$\lambda_t = a\ \theta^{\,b}\,\mathrm{Fr}^{\,c}\left(\frac{d_p}{D}\right)^{d}\left(\frac{\rho_p}{\rho_f}\right)^{e} \tag{2}$$

Using this simple model in the acceleration region, Pinho (1999) demonstrated through the analysis of an elemental portion of conveying pipe and integrating the result through the acceleration length that,

$$\left(\frac{L_{ac}}{D}\right) = \alpha\ \theta^{\,\beta}\,\mathrm{Fr}^{\,\gamma}\left(\frac{d_p}{D}\right)^{\delta}\left(\frac{\rho_p}{\rho_f}\right)^{\eta} \tag{3}$$

Knowing the experimental data of L_{ac}/D, for different tested situations covering several stoppers diameters d_p and densities ρ_p, loading factors θ and air interstitial velocities U_f (necessary to calculate the Froude number $Fr = U_f/\sqrt{g\ D}$), these data were correlated through dimensionless numbers, as shown in Eq. (3). The fitting parameters α, β, γ, δ and η, are obtained through the application of a commercial software for nonlinear regression analysis.

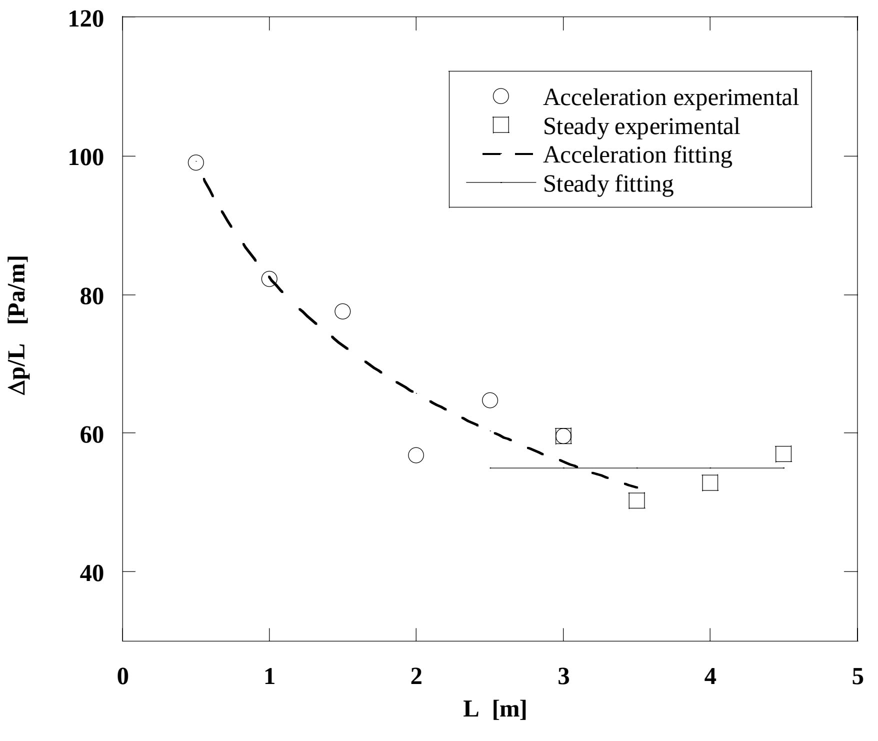

Figure 4. – Definition of the acceleration length.

To determine the acceleration length for each experimental run in an objective way, the pressure drop per unit length for each run was plotted versus the pipe length for each tested situation; two fitting lines were also obtained, one logarithmic concerning the acceleration region and another linear and constant for the steady state conveying region. The intersection of both lines defined the acceleration length. Figure 4 presents an example concerning a given experiment for 38×22 stoppers. This procedure was adopted for all tested situations. The obtained acceleration lengths are of the same order of magnitude of those found in horizontal pneumatic conveying of cork stoppers, Pinho (1999).

After obtaining the acceleration lengths, the fitting of these values according to the formulation of Eq. (3) gave the following result,

$$\left(\frac{L_{ac}}{D}\right) = 0.4178\ \theta^{\,0.02163}\,\mathrm{Fr}^{\,-0.1238}\left(\frac{d_p}{D}\right)^{2.577}\left(\frac{\rho_p}{\rho_f}\right)^{1.601} \tag{4}$$

which is plotted in Fig. (5) against the corresponding experimental values.

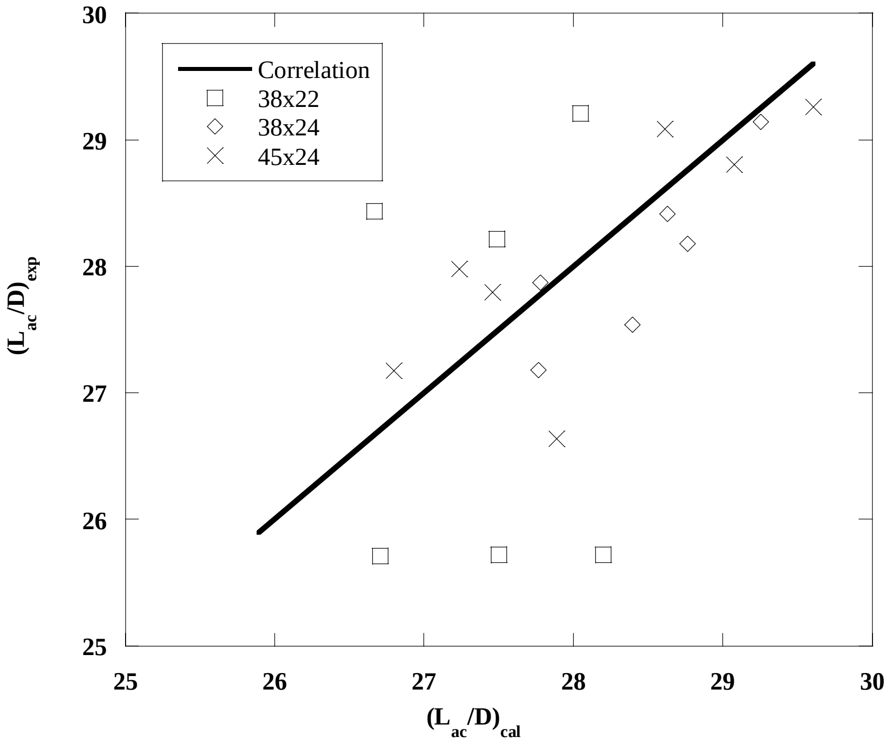

Figure 5. - Comparison between experimental and calculated values for the acceleration length.

The maximum absolute deviation between experimental $\left(L_{ac}/D\right)_{exp}$ and calculated data $\left(L_{ac}/D\right)_{exp}$ with this formula is of 13 % whereas the mean deviation, calculated through,

$$\text{Mean Deviation, \%} = \left[\sqrt{\sum \left(\frac{\left(\mathrm{L_{ac}/D}\right)_{cal} - \left(\mathrm{L_{ac}/D}\right)_{exp}}{\left(\mathrm{L_{ac}/D}\right)_{exp}} \right)^2 \Big/ \mathrm{N}} \right] \times 100 \tag{5}$$

as defined by Wen and Chen (1982), is 7 %. In the above equation N is the number of experiments that were carried out and whose data were used in the calculations.

If an alternative and more elegant correlation is adopted through the use of rounded values for the fitting parameters α, β, γ, δ and η, the result is

$$\left(\frac{L_{ac}}{D}\right) = \frac{21}{50}\,\theta^{11/500}\,\mathrm{Fr}^{-5/40}\left(\frac{d_p}{D}\right)^{13/5}\left(\frac{\rho_p}{\rho_f}\right)^{8/5} \tag{6}$$

For this last correlation the maximum absolute deviation between experimental $\left(L_{ac}/D\right)_{exp}$ and calculated data $\left(L_{ac}/D\right)_{exp}$ with Eq. (6), is of 16 %, while the mean deviation calculated again through Eq. (5) is again of 7 %.

For these results of Eqs. (4) and (6), three stoppers sizes were used as referred in Tab. 1. Tested loading factors covered the range from 0.10 to 0.35, the air flow Reynolds number ($\mathrm{Re} = \rho_f U_f D / \mu_f$) went from 1.3×10^5 to 2.6×10^5, while the Froude number ranged from 15.3 to 30.7, all values typical of cork stoppers conveying systems. In the definition of the Reynolds number, μ_f is the air dynamic viscosity. Small loading factors are common in the pneumatic conveying of stoppers, because of the combined influence of having to transport large particles with the use of centrifugal fans having flat working curves, promoting flow blockage situations, Wirth and Molerus (1986). This affects minimum conveying conditions and limits the maximum possible loading factor. At the same time, the extreme fragility of stoppers imposes some restrictions on the maximum recommended transport velocity, reducing even further the range of working conditions.

4. Conclusions

From the study on vertical pneumatic conveying of cork stoppers it was realised that the order of magnitude of the acceleration length is identical to that of horizontal conveying. A simple empirical correlation for the acceleration length was proposed and by sacrificing a little of the accuracy of the original correlation, a more elegant second one can be obtained through the use of rounded fitting parameters.

Future work will be carried out on the characterization of the influence of the preceeding curve, upon the definition of the subsequent vertical acceleration length.

5. Acknowledgements

The authors of this work are thankful to INEGI – Instituto de Engenharia Mecânica e Gestão Industrial for allowing the installation of the experimental setup in its laboratories.

6. References

Barbosa, R. and Pinho, C., 2004, "Dilute Phase Vertical Pneumatic Conveying of Cork Stoppers", Proceedings of the 10th Brazilian Congress of Thermal Sciences and Engineering, ENCIT 2004, (CIT04-0085.pdf), 29th November to 3rd December 2004, Rio de Janeiro, RJ, Brazil.

Barth, W., 1960a, "Physical and Economical Aspects of Transportation of Solids in Fluids and Gases", (In Germany), CIT 32, No. 2, pp.164-171.

Barth, W., 1960b, "Technical Flow Problems in Conveying Dust and Gas Mixtures", (In Germany), Mitt. VGB., No. 79, p.238-244.

Dzido, G., Palica, M. and Raczek, J., 2002, “Investigations of the acceleration region in the vertical pneumatic conveying”, Powder Technology, Vol. 127, pp. 99-106.

Fan, L. S., and Zhu, C., 1998, “Principles of Gas-Solid Flows”, Cambridge University Press, Cambridge Series in Chemical Engineering, Cambridge.

Klinzing, G. E., 1981, “Gas-Solid Transport, McGraw-Hill Book Company.

Lee, W. K., Vaseleski, R. C. and Metzner, A. B., 1974, “Turbulent Drag Reduction in Polymeric Solutions Containing Suspended Fibres”, A.I.Ch.E. Journal, Vol. 20, No.1, pp. 128-133.

Marcus, R. D., Hilbert Jr., J. D, and Klinzing, G. E., 1985, “Flow Through Bends and Acceleration Zones in Pneumatic Conveying Systems”, ", Bulk Solids Handling, Vol. 5, No. 4, pp. 121-126.

Marcus, R. D., Leung, L. S, Klinzing, G. E. and Rizk, F., 1990, “Pneumatic Conveying of Solids.”, Chapman and Hall, London.

Namkung, W. and Cho, M., 2002, “Pressure Drop in a Vertical Pneumatic Conveying of Iron Ore”, Ind. Eng. Chem. Res.,Vol. 41, pp. 5316-5320.

Neto, P. and Pinho, C., 1998, “Dilute Phase Horizontal Pneumatic Conveying of Cork Stoppers: A Preliminary Experimental Study”, Proceedings of the Symposium on Thermal and Fluids Engineering, CSME Forum SCGM, 19th-22nd May, Toronto, Vol. 1, pp. 360-367.

Pinho, C., 1999, “Acceleration of Cork Stoppers in Pneumatic Conveying”, 15th Brazilian Congress of Mechanical Engineering, 22nd to 26th November, Águas de Lindóia, São Paulo, SP, Brazil.

Pinho, C., 2001, “Horizontal Pneumatic Conveying of Cork Stoppers”, Proceedings of Cobem 2001, Fluid Mechanics, Vol. 8, pp 21-29. 16th Brazilian Congress of Mechanical Engineering, 26th to 30th November 2001, Uberlândia, MG, Brazil.

Raczek, J. and Palica, M., 1997, “Selection of the gas working velocity in vertical pneumatic conveying systems for binary mixtures”, Chemical Engineering and Processing, No. 36, pp. 167-170.

Radin, I., Zakin, J.L. and Patterson, G.K., 1975, "Drag Reduction in Solid-Fluid Systems", AIChE Journal, Vol. 21, No.2, pp. 358-371.

Rautiainen, A., Stewart, G., Poikolainen, V. and Sarkomaa, P., 1999,“An experimental study of vertical pneumatic conveying”, Powder Technology, Vol. 104, pp 139-150.

Rhodes, M., 1998, “Introduction to Particle Technology”, John Wiley and Sons, Chichester.

Rose, H.E. and Duckworth, R. A., 1961, “Transport of Solids Particles in Liquids and Gases”, The Engineer, No. 14, 21 to 28 March.

Smeltzer, E. E., Weaver, M. L. and Klinzing, G. E., 1982, "Pressure Drop Losses due to Electrostatic Generation in Pneumatic Transport", Ind. Eng. Chem. Process Des. Dev., Vol. 21, No. 3, pp. 390-394.

Szikszay, G., 1988, "Friction Factor for Dilute Phase Pneumatic Conveying", Bulk Solids Handling, Vol. 8, No. 4, pp. 395-399.

Weber, M., 1991, "Friction of the Air and the Air/Solid Mixture in Pneumatic Conveying", Bulk Solids Handling, Vol. 11, No. 1, pp. 99-102.

Wen, C.Y. and Chen, L.H., 1982, “Fluidized Bed Freeboard Phenomena: Entrainment and Elutriation”, AIChE Journal, vol. 28, No. 1, pp. 117-128.

Wirth, K.-E. and Molerus, O., 1986, "Solids and Gas-Solid Flows", Encyclopaedia of Fluid Mechanics, Vol. 4, Ch. 15, pp. 471-484 N. P. Cheremisinoff Editor, Gulf Publishing Company.

Xu, G., Nomura, K., Gao, S. and Kato, K, 2001, "More Fundamentals of Dilute Suspension Collapse and Choking for Vertical Conveying Systems", AIChE Journal, Vol. 47, No. 10, pp. 2177- 2196.

Yang, W. and Keairns, D.L., 1973, "Estimating the Solid Particle Velocity in Horizontal Pneumatic Conveying Lines", The Canadian Journal of Chem. Eng., Vol. 51, pp. 779-781.

Yang, W., 1973, "Estimating the Solid Particle Velocity in Vertical Pneumatic Conveying Lines", Ind. Eng. Chem. Fundam., Vol. 12, No. 3, pp. 349-352.

Yang, W., 1974, "A Correlation for Solid Friction Factor in Vertical and Horizontal Pneumatic Conveying", AIChE Journal, Vol. 20, No. 3, pp. 605-607.

Yang, W., 1975, "A Mathematical Definition of Choking Phenomenon and a Mathematical Model for Predicting Choking Velocity and Choking Voidage", AIChE Journal., Vol. 21, No. 5, pp. 1013-1015.

Yang, W. and Keairns, D.L., 1976, "Estimating the Acceleration Pressure Drop and Particle Acceleration Length in Vertical and Horizontal Pneumatic Transport Lines", Pneumotransport 3. Third International Conference on the Pneumatic Transport of Solids in Pipes, 7^{th} - 9^{th} April, pp. D7-89 - D7-98.

Yang, W., 1978, "A Correlation for Solid Friction Factor in Vertical Pneumatic Conveying Lines", AIChE Journal, Vol. 24, No. 3, pp. 548-552.

6. Responsibility notice

The authors are the only responsible for the printed material included in this paper.