Designing of atomized slip pneumatic conveying plant in ceramic industry by a simulator and experimental tests.

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Abstract: Nowadays, in the ceramic industry, atomized slip is transferred mainly by belt conveyors. This kind of transport, also when the plant is equipped by specific powder confinement devices, spread out fine particles in the working environment, generating a serious risk for worker's health. Atomized slip pneumatic conveying fully solves dust pollution problem in industrial environment, but some fluid-dynamic parameters need to be controlled to ensure that the atomized slip had the characteristics required by the following processing.
This paper shows how to design the pipeline by a simulator (TPSimWin) able to evaluate, step-by-step, the characteristic parameters of the two-phase flow in every section of the piping, such as pressure losses, air and solid speed and gradient, voidage ratio.
Moreover, several experimental tests have been carried on by means of a full scale layout facility. The first step consisted in the fluid dynamic characterization of the atomized slip particles and, afterword to define the best operating conditions for pneumatic conveying, in dense phase, in order to preserve particle integrity and humidity.

Keywords: pneumatic conveying, dense phase, simulation software, ceramic industry

1. Introduction

In the field of ceramic industry, atomized slip is transferred mainly by belt conveyors, which move the material from the spray dryer bottom to the warehouses and from the latter to the presses. Belt conveyors are a very simple and reliable system, able to ensure atomized slip integrity without significantly changing its humidity content during the transport. These two aspects are fundamental at an industrial level: product fragmentation or its excessive drying/humidification make the atomized slip unusable for the future production of tiles (Bianchini *et al.*,2015a).

On the other hand, there are also several problems related to the use of belt conveyors that must be considered. First, this kind of transport, usually without a specific confinement device, releases fine powders into the environment, generating a serious risk for workers' health (Hughes *et al.*,2001; Başaran *et al.*, 2002). In fact, the long distances covered by the belts cause a lengthy exposure of the atomized slip in the working environment, so it is very difficult to avoid the diffusion of fine particles, which increases with the belts speed. To cope with this problem, companies are forced to install very expensive air extraction systems, increasing both capital and management costs (Bianchini *et al.*, 2014; Bianchini *et al.*, 2015b). Moreover, long distances means high dimensions, with consequent strong constrains on the layout of the plant, due to belt conveyors obstruction: the need for change is very urgent.

Pneumatic transport is an innovative solution to industrial problems related to bulk solid transport. This technology, thanks to a complete confinement of atomized slip during all the transport phases, fully solves dust pollution problem in the working environment. At the same time, pneumatic conveying has lower costs compared to the current technology (air suction plants are not necessary) and the lay-out design is complete free from constraints (Saccani *et al.*, 2008).

However, to guarantee product integrity, maximum solid velocity and speed gradient must be limited. Product wear occurs as result from friction with the inside wall of the piping, from the collisions against bends and from simply collisions between particles. As regards, it must be emphasized that atomized slip is very fragile. In fact, due to the particular process of spray drying, atomized particles are not spherical but they presents an internal concavity. Fig. 1 shows a macro photo of atomized slip particles, whose size ranging between 100 and 600 μm.

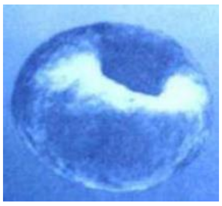

Figure 1: Enlargement 300:1 of atomized slip.

This paper shows how design a pneumatic conveying plant using the TPSimWin, a software simulator able to foreseen the behavior of two-phase flow where solid particles are conveyed by gaseous stream. The iterative procedure for characterization of solid material is described, in which the computational results provided by the TPSimWin are compared with the results obtained from experimental tests. The characteristic parameters of the atomized slip determined with this procedure will then be used by TPSimWin. On the basis of the software forecasts, the optimal transport conditions will be identified, defining pipeline diameter and solid loading ratio capable to minimize total pressure loss and, at the same time, preserve atomized slip integrity and humidity. Solid loading ratio m is defined as the ratio between the mass flow rate of solid and air.

Experimental tests have been carried out on a specifically designed pneumatic conveying test facility, that will be described in section 2.

A number of test have already been performed on this plant in previous studies, with the aim of identifying in which operating conditions the pneumatic system is able to convey a constant flow of atomized slip in plug type mode of dense phase, avoiding critical problems of product damage and humidity. The achieved results have been proven that maximum solid and air velocity, which are strictly linked, need to be limited. The maximum solid speed must remain below the limit value of 7 m/s during all the transport, while the maximum velocity gradient admissible is 8 s^{-1}. Therefore, the solid loading ratio has a key role in guaranteeing product integrity during the transport process (Bianchini *et al.*, 2015a; Bianchini *et al.*, 2019).

2. Experimental procedure

2.1 Simulator software TPSimWin

TPSim Win is a computational software that simulates two-phase flow in which solid or liquid particles are conveyed by gaseous stream. TPSimWin is able to foresee all two-phase flow characteristics and conveying stability, describing the physical phenomenon with a good accuracy. Step-by-step calculation method used by TPSimWin is based on the fundamental equations of mechanics and fluid dynamics. Solid particles distribution inside the circular pipe is assumed homogeneous and their granulometry constant and uniform. The following are the five fundamental equations:

1) Gas continuity equation: $v = \frac{4G}{(\pi D^2 e m \rho_f)}$

2) Solid continuity equation: $c = \frac{4G}{[\pi D^2 (1-e)\rho_s]}$

3) Gas state equation: $\frac{p}{\rho_f} = costant$

4) Differential equation of motion:

$$\frac{dc}{dl} = \frac{3}{4}\frac{c_w}{d_s}\frac{\rho_f}{\rho_s}\frac{(v-c)^2}{e\,c} - \frac{1}{c}\left(g\sin\beta + \lambda_s\frac{c^2}{2d}\right) + \frac{\rho_f}{c\,\rho_s}\left(g\sin\beta + \lambda_f\frac{v^2}{2d} + v\frac{dv}{dl}\right) + \frac{1-e}{e}\frac{\rho_s-\rho_f}{\rho_s}g\frac{w_s}{c\,v}cos^2\beta$$

5) Pressure loss equation:

$$-\frac{dp}{dl} = e\left(\rho_f g \sin\beta + \lambda_f \frac{\rho_f}{2}\frac{v^2}{d} + \rho_f v \frac{dv}{dl}\right) + (1-e)\left[(\rho_s - \rho_f) g cos^2\beta \frac{w_S}{v} + \rho_s g \sin\beta + \lambda_s \frac{\rho_s}{2}\frac{c^2}{d} + \rho_s c \frac{dc}{dl}\right]$$

Legend

c = solid speed	p = pressure
c_W = drag coefficient of the particle	v = gas speed
d = pipeline diameter	w_s = fall speed of the particle
ds = particle diameter	β = angle of inclination of the pipe
e = voidage ratio	λ_f = friction coefficient of gas
g = gravity acceleration	λ_s = friction coefficient of solid
G = solid mass flow rate	ρ_f = gas density
l = length	ρ_s = solid density
m = solid loading ratio	

In order to start the algorithm, the user have to enter a series of data related to the features of the plant, to pipeline geometry and to solid-gas mixture. The width of calculation steps must be specified for each section of the plant. About solid particles, their fundamental fluid dynamic characteristics are defined by three parameters: hydraulic diameter, straight friction coefficient and bend friction coefficient. Hydraulic diameter is the theoretical diameter of a spherical particle characterized, in actual condition, by the same fluid dynamic behaviour. Friction coefficients include particle-particle, particle-wall and particle-gas friction. Once all the parameters have been introduced, TPSimWin provides us both a spreadsheet and a diagram wherein solid and air velocity, total pressure loss and voidage ratio are expressed as a function of pipeline length (Fig.2). TPSimWin is also able to produces a second kind of diagram, related to pneumatic conveying stability, where total conveying pressure drop is expressed as a function of starting pressure (Fig.3) (Saccani, 1992; Saccani, 1993; Saccani, 1996; Saccani, 2005; Amati *et al.*, 2005).

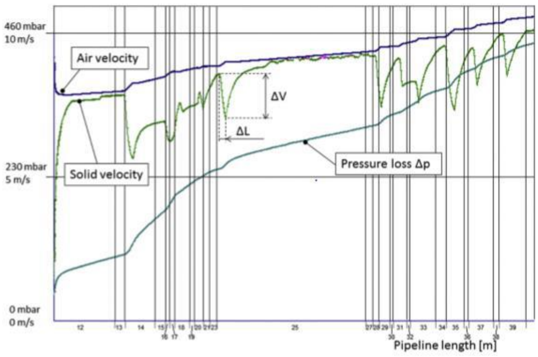

Figure 2: Typical TPSim Win output diagram.

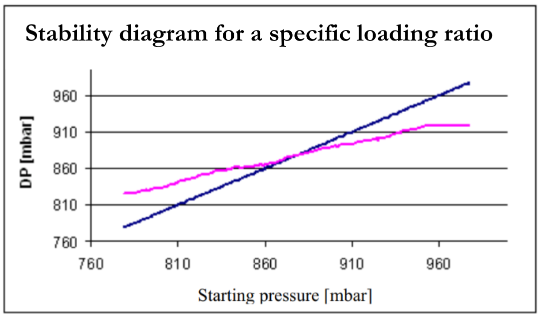

Figure 3: Typical TPSim Win stability diagram.

The intersection between the magenta line that characterizes the plant and blue line corresponding at a value of starting pressure, defines the point of U diagram that describes pressure drop as a function of loading ratio m (Bianchini et al., 2010). TPSimWin can be used to foreseen particles behaviour in different condition like, for example, in dense and diluted phase and in fixed, bubbling and circulating fluidized bed. The ability to predict with good accuracy the two-phase flow during a pneumatic transport is a fundamental question to optimize plant design both from technical and economical point of view. Using TPSimWin, this ability is closely linked to the knowledge of the three parameters that characterize solid particles. For this purpose, an atomized slip pneumatic conveying test facility has been designed and realized in industrial size. Along the pipe, several pressure transducers have been installed to check, by a monitoring system, pressure drop conveying. In fact, if particles and gas mass flow rate are known, their characteristic fluidynamic parameters can be defined by pressure drop trend along the pipeline.

2.2 Test facility

The atomized slip pneumatic conveying test facility is an experimental plant designed in industrial scale. General lay-out of the plant is reported in Fig. 4: the whole circuit, about 70 m long, has 11 bends, a long straight section and a vertical one. Internal diameter of the pipeline is 85 mm. Test facility P&I is shown in Fig.5. Air mass flow rate is measured by a differential pressure (DPZ), together with air density that is computed by pressure (PL) and temperature (TZ) transmitters. Atomized slip pneumatic conveying starts at the rotary valve (MSL), which introduces the solid material inside the circuit. Atomized mass flow rate is regulated by means of an inverter (INMSL) and it is measured by load cells (JBB). A bag filter (B) clean the air at the end of the transport process, then the atomized slip can be discharged or recirculated. Moreover, pressure and temperature of pneumatic conveying are monitored all along the pipeline, thanks to 8 differential pressure transmitters (PD#), 29 pressure connections and 12 temperature transmitters (T#L). 8 "Multiplexer" system (QMP#) manage pressure data acquisition. Every multiplexer is composed of a differential pressure transmitter, a maximum of 4 pressure connections and for each of them a pair of solenoid valve. This system is able to switch, in a temporal sequence, the differential pressure signal from one connection to another, by alternate opening of a solenoid valve pair. In this way it is possible to have a complete mapping of the pressure drop along the pipeline, using a limited number of differential pressure gauge. In addition, the test facility is equipped with PC software that acquires and memorizes signals from transducers.

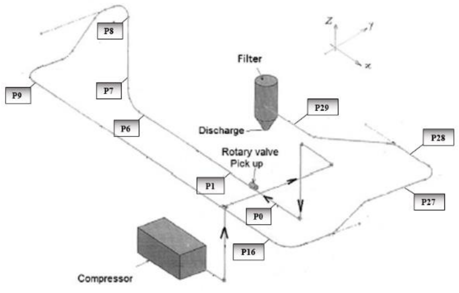

Figure 4: Test facility lay-out.

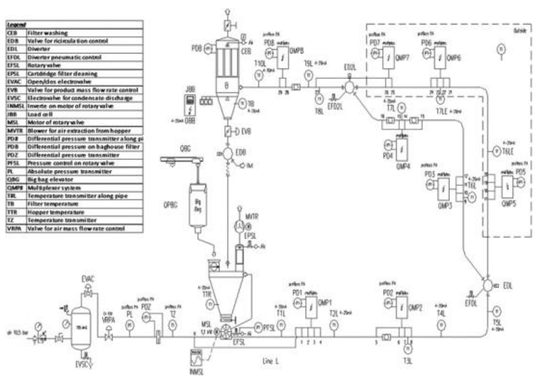

Figure 5: Test facility P&I.

2.3 Characterization of atomized slip

The characterization of atomized slip is an iterative process aimed at determining three characteristic parameters: straight friction coefficient, bend friction coefficient and hydraulic diameter. These parameters are used by TPSimWin to simulate the transport process, so that their knowledge is necessary to design an industrial plant. First, a pneumatic transport is carried out in the test facility. Starting pressure, solid and air mass flow rate are fixed and known. Thanks to numerous instruments installed throughout the line, we also know the trend of pressure drop all along the circuit. So, for each conveying test we can plot an experimental diagram where pressure values are represented as a function of pipeline length. An example is shown in Fig.6.

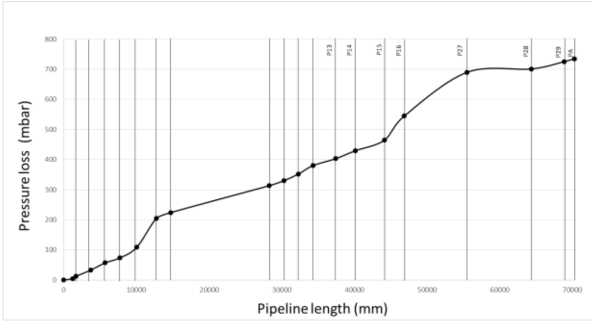

Figure 6: Pressure drop is plotted as a function of pipeline length.

Then, the transport process carried out in the test facility is simulated by TPSimWin. All the required input data are known, except for the three parameters we want to determine. Therefore, first attempt values are used in the first simulation. Comparing the pressure diagram provided by TPSim Win with the experimental one, it is possible to evaluate how revise the three values. In fact, the slope of the pressure curve in the straight sections of the plant (trait from P9 to P16 in the lay-out of Fig.4, for example) is directly linked to the straight friction coefficient. In the same way, pressure loss trend along curved sections depends on the bend friction coefficient. Once the parameters have been adjusted, a new simulation is run. Computational and experimental pressure diagram are compared again. Proceed in this way until the two curves are sufficiently similar. At the end of this procedure, the parameters just found must be verified. So, others conveying test and simulations are performed, changing conveying operative conditions.

3. Experimental results and discussion

Technical characteristics (mass flow rate and loading ratio) will be described by dimensionless values to protect the know-how emerging from experimental tests. In particular, the solid and air mass flow rates varied from the maximum value (dimensionless value = 1) to half of these (dimensionless value = 0.5). Solid loading ratio varied between dimensionless values of 1 to 0.55.

3.1 Characterization of atomized slip

A transport test was carried out on the test facility, with a solid loading ratio m/m_{max} = 0.85. Solid mass flow rate was set at dimensionless value of 0.8. The same conveying process was then simulated by TPSim Win, varying the input values of hydraulic diameter, straight friction coefficient and bend friction coefficient until computational pressure diagram is strongly agrees with the experimental points. This condition, shown in Fig.7, has been reached using the following input values:

- hydraulic diameter = 0.092 mm
- straight friction coefficient = 0.001
- bend friction coefficient = 0.1

Green line is plotted by the software, whereas black points are experimentally obtained from pressure transducers.

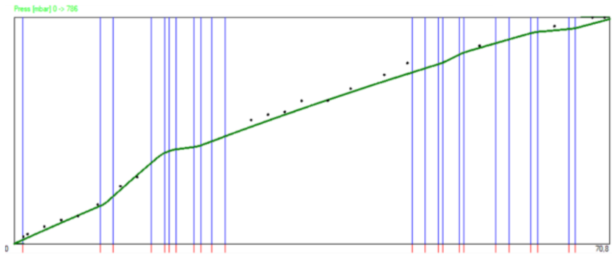

Figure 7: Pressure drop calculated by TPSim Win (green line) and experimental values (black points) are plotted as a function of pipeline length.

Whit the aim to verify their accuracy, these three parameters have been used to simulate several others conveying test, in different operating conditions. Solid and air mass flow rate and transport pressure have been changed. For all the tests, the trend of the pressure drop foreseen by TPSim Win has been compared with the experimental values obtained from the test facility. In the vast majority of cases, the results expected by TPSim Win have proven to be very close to the experimental results.

3.2 Industrial plant design

After determining the characteristic parameters of the atomized slip through the iterative procedure described above, it is possible to proceed with the design of the conveying plant using the TPSim Win simulator.

The industrial plant to be designed must be able to transport a quantity of atomized slip up to 30000 Kg/h. The overall length of the line is 54.5 m.

The first designing phase consist in defining the diameter of the pipe. Three simulations were carried out by TPSim Win using three different diameter sizes: 190 mm, 215 mm and 240 mm. The result is shown in Fig. 8, where total pressure loss Δp is expressed as a function of dimensionless solid loading ratio m/m_{max}.

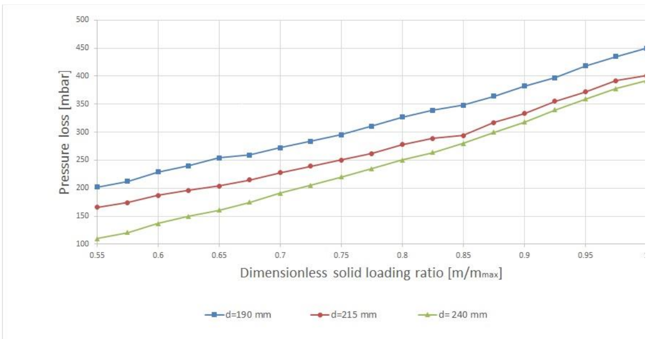

Figure 8: Total pressure loss Δp expressed as a function of dimensionless solid loading ratio m/m_{max} for different values of pipeline diameter size.

The figure immediately shows that the configuration with a 190 mm diameter generates higher pressure loss if compared with the other two solutions. The choice of a 240 mm diameter size develops lower pressure loss than the 215 mm, in the range of solid loading ratio between 0,55 and 1.

On the other side, the pressure loss curve of the 215 mm diameter size is more flat than the other one, and for this reason it is more suitable. In fact, the 215 mm diameter size has been chosen because of its more flexibility: in this configuration the plant can work with different values of solid loading ratio in a smaller range of pressure drop. This means a more stable system.

Once the diameter size is defined, TPSimWin is a very useful tool also in the choice of solid loading ratio, by foreseeing the trend of solid velocity and solid speed gradient. The results in Fig. 9 show how, with a solid loading ratio $m/m_{max} = 0.68$, in the final section of the line solid velocity reach and exceed the limit of 7 m/s. Total pressure loss during the transport process is 205 mbar. Increasing the solid loading ratio to $m/m_{max} = 0.93$ (Fig.10) total pressure loss increase up to 355 mbar, while maximum solid speed decrease to about 5 m/s, well below the typical values in which atomized slip fragmentation occurs. Increasing further the solid loading ratio, pressure loss raise strongly. Therefore, optimal value for dimensionless solid loading ratio is in the range 0.88 – 0.93.

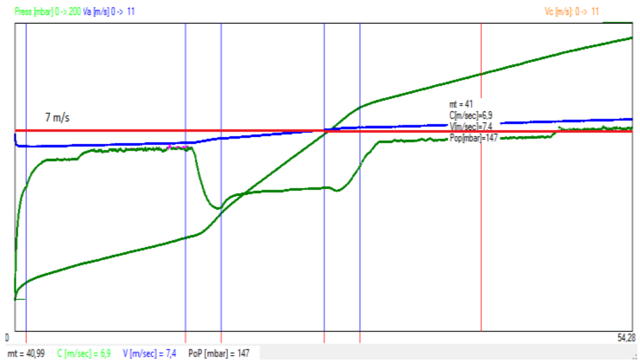

Figure 9: Simulation result by TPsim Win. Pressure loss (dark green line), solid velocity (green line) and air velocity (blu line) are plotted as a function of pipeline length, with a solid loading ratio $m/m_{max} = 0.68$ and a duct internal diameter of 215 mm.

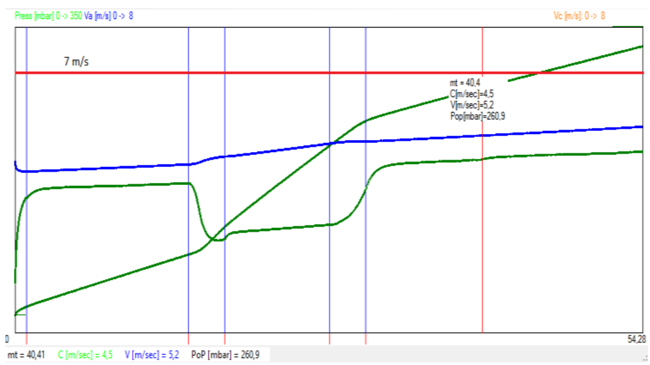

Figure 10: Simulation result by TPsim Win. Pressure loss (dark green line), solid velocity (green line) and air velocity (blu line) are plotted as a function of pipeline length, with a solid loading ratio $m/m_{max} = 0.93$ and a duct internal diameter of 215 mm.

3.3 Results discussion

The results provided by TPSim Win clearly show that dense phase is the only suitable method for atomized slip pneumatic conveying. In fact, in a transport process in dilute phase, a great amount of air is used to move the particles, and gas and solid speed are relative high. This leads to problems related to atomized slip fragmentation. Furthermore, working with high air volume it becomes very difficult to avoid solid drying or humidifying due to the interaction with conveying air. If the solid loading ratio is very high, instead, this problems is almost negligible. Software simulator also shows if there are critical points in the circuit where solid velocity reach a value greater than the air velocity, with the risk of transport blockage. Tanks to TPSim Win we are able to define technical and economical characteristics for plant optimization . As regards, it is possible to define several operating conditions as a function of solid loading ratio, setting design solid flow rate and changing air flow rate. From an economic point of view, it is important to note that air flow rate variation involves not only compressor and final filter variation, but also piping diameter variation. This means a change in conveying pressure drop, which is the most important variable to define conveying stability. Therefore, to optimaze plant design, we need to plan and compare some different configuration with several air flow rates and piping diameters.

4. Conclusions

This paper presents TPSimWin software simulator, which has proved to be an excellent instrument for technical and economical optimization analysis in a conveying plant design. Pneumatic test facility is described: this plant was built to test atomized slip pneumatic conveying and to confirm TPSim Win simulation forecasts. Moreover, the iterative procedure of characterization of solid material is shown, aimed at determining the values of hydraulic diameter, straight friction coefficient and bend friction coefficient for the atomized slip. Pneumatic conveying test facility can be exploited to characterize any kind of bulk solid material.

Finally, TPSimWin was used in designing of an industrial pneumatic conveying plant, to define pipeline diameter and to choose the optimal value of solid loading ratio. Computazional results provided by TPSimWin are very usefull tool to identify the best operative conditions, in which product integrity is ensured and total pressure losses are minimized.

It is the first time that this kind of material is pneumatically conveyed without fragmentation and dehydration. This is a fundamental step towards industrial development of pneumatic transport systems for atomized slip in ceramic industry.

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