Consideration about Lateritic Mineral Pneumatic Conveying in Dense Phase

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Abstract - In the nickel companies, the pneumatic conveying has been limited by the excessive energy expense that reaches the 18, 82 MJ/T. The causes that originate this difficulty are: the incorrect selection of the gas transporter speed, the existence of the feeders numberless and the infinite variety of physical and aerodynamic characteristics of the materials to transport that lead to the inaccuracy of the pneumatic conveying projects. Starting from the existent knowledge for the solids pneumatic transport in flowed and dense phases a descriptive theoretical model is deduced whose parameters (difference of speed between the gas and the solid and flotation speed) are obtained with data of an experimental installation. To obtain the parameters of the pattern is used the method of solution differential equations Runge - Kutta fourth order, like part of a procedure iterative that it leads to the minimization of the average error module between the experimental values and the predicted for the pattern. With the employment of the pattern it is simulated the dependence of the pressure losses, the solid flow and the concentration of the mixture in function of the gas flow of the lateritic mineral pneumatic transport systems. The reduction of the losses pressure with the increment of the speed fluid is confirmed in values less than 6,12 m/s in the horizontal transport and 5,21 m/s in the vertical one. The transport in continuous dense phase extends until the 18 m/s in both cases.

Keywords - Pneumatic conveying, mathematical model, flowed and dense phases
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I. INTRODUCTION

The mathematical modeling is a necessary tool in the design and operation of the processes plants. The simulation, using these techniques, is an efficient way for the evaluation and optimization [1] of the technological processes and industrial facilities. Mason et al [8], develop the simulation of pneumatic conveying systems to increasing the flexibility of the design methods. The software use like the MATLAB and ANSYS offer the possibility to select a wide range of numeric methods to solve the equation systems of the models with accurately appropriate.

The modeling of two-phase air-solid mixtures is a complex task due to the different concentrations in weight of the elements. The existence of different types of flows requires different types of models [20]. The models of dilute and dense phase transport not only are important in pneumatic conveying, also in other applications like the fluidization and hydraulic processes.

The Punta Gorda plant is one of the main Cuban minerals industries. This plant processes the lateritic ores of the northeast in the island. The pneumatic conveying is carried out after the drying and mill process of the minerals [11].

The length of pneumatic conveying systems is smaller than 400 meters. The main problems are: the drop concentration of the transported mixture (15,9 kg of solid/ m3 of air) and the absence of procedures for the projection, selection and calculation of the rational parameters [20].

The pneumatic conveying systems, like investigation object, can be divided in three parts: feeding systems, transport systems, reception and separation systems.

Hui and Tomita [5] study the behavior of particle speed and concentration profile in horizontal pipes using technical of photographic images. Yamamoto and Tanaka [22] carry out an analysis of the particles trajectory by means of the direct simulation. These techniques were used for Miyoshi et al [12, 13]; ignoring the effect that can produce the air flow.

However, Raheman and Jindal [16] consider the effect of mixture flows determining the slip speed (differs between the speed of the gas and the speed of the material) in the transport of two-phase fluids.

The model presented by Massoudi and Rajagopal [9] describes the behavior of mixture particles flow in dense phase, and analyze the influence of the collisions inter-particles, the coefficient of friction, the viscosity and the development of isothermal flow.

Pan and Wypych [15] develop a model of materials pneumatic transport in irregular shape in dense phase taking in consideration the theoretical modeling in horizontal and vertical pipes; the model considers the pressure losses in the transport line. A similar investigation for the fluid phase was reported by Lampinen [6].

Hettiaratchi and Woodhead [4] make a comparison among the pressure losses in horizontal and vertical pipes starting from the correlations and they get to minimize the quantity of experiments for the evaluation of the different systems.

Pacheco [14] and Lesme [7] based on theoretical and empiric knowledge proposes a calculation methodology for the projection and selection of bagasse pneumatic transport for horizontal and vertical pipes, also the losses in elbows. Mason et al [8] and Sommerfeld [18] get the solution of the movement of two-phase systems using the equations of mass, moments and energy balance.

About the lateritic ore, the works carried out isolated elements of pneumatic conveying systems, without completing the group of necessary knowledge to project, select and evaluate these installations. This imposes the necessity to execute an investigation that contributes to the main efficiency in the current systems of pneumatic transport in the nickel industry with ammonia technology.

The objective of the article is to obtain a mathematical model of lateritic mineral pneumatic conveying for the selection of the rational parameters under certain work conditions.

II. MODEL DEVELOPMENT

The model development for lateritic mineral pneumatic conveying in dilute and dense phases in horizontal and vertical pipes is elaborated starting from the simultaneous use of mass, momentum and energy balance equations. For it is considered a pipeline with δ angle from the horizontal shown in figure 1.

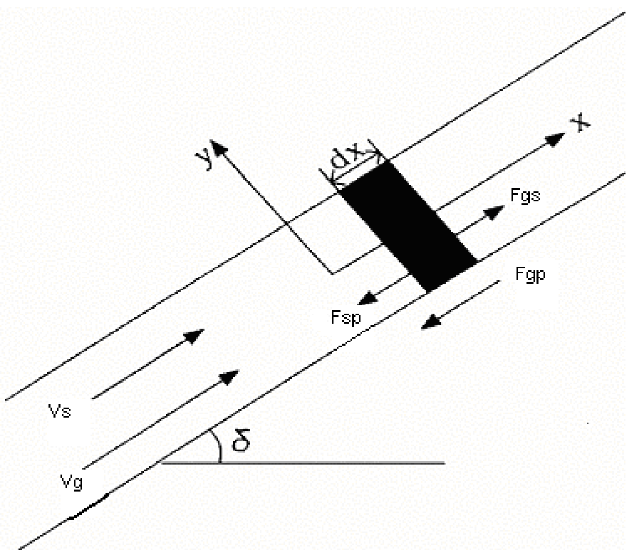

Figure 1. The friction forces that affect the movement of the gas-solid mixture during the pneumatic transport.

The “dx” element shown in figure 1 contains the air flow and lateritic mineral particles, the partial densities are represented for ρ_g and ρ_s, respectively; and their porosity is expressed for Ɛ. If the air pressure is P, the force per area unit of the total mixture that affects the air flow is Ɛ.P and the force per area unit that affects the mineral flow is (1- Ɛ)P.

The momentum balance equation for the solid particles in the direction of the x-axis is (equation 1):

$$\rho_s \frac{dV_S}{dt} = -\frac{d}{dx}\left[(1-\varepsilon)\cdot P\right] - \rho_s \cdot g \cdot sen\delta - Fsp + Fgs \tag{1}$$

Where:

ρ_s - lateritic mineral density, kg/m^3

Ɛ - average voidage

P- air pressure, Pa.

F_{sp}- friction specific forces caused by the interaction between the particles and the particles with the walls of the pipes, N/m^3

F_{gs}- specific force of interaction between the air and the lateritic mineral, N/m^3

Vs – solid velocity, m/s

The momentum balance equation for the air flow in the direction of the x-axis is

$$\rho_g \frac{dV_g}{dt} = -\frac{d}{dx}(\varepsilon \cdot P) - \rho_g \cdot g \cdot sen\delta - Fgp - Fgs \tag{2}$$

Where:

ρ_g - air density, kg/m^3.

Fgp – friction specific force caused by the walls, N/m^3.

Due to the mineral particles vibrate along the y-axis, changes internal velocity profile of the air; the expression of the friction force is different to the force for an empty tube. The friction force Fgp (equation 3) is a combination of the air friction force with the wall without the presence of particles and the specific force caused by the vibration of the mineral particles.

$$Fgp = \frac{\lambda_G}{D} \cdot \frac{\rho_g}{2} \cdot V_g{}^2 + F_V \tag{3}$$

Where:

F_v- especific force due to the mineral particle vibration, N/m^3

λ_G - gas friction coefficient

D- tube diameter, m.

Vg- gas velocity, m/s.

To model the force F_v is applied the virtual power method, this implies the flotation effect and the fall of the particles toward the bottom of the tube [8].

The power per unit volume (W/m^3) needed to keep the particles floating in the direction of the y-axis is:

$$P_v = \rho_s \cdot g \cdot \cos\delta \cdot V_f \cdot \cos\delta \tag{4}$$

The relationship between the virtual power and the force F_v is expressed by the equation (5):

$$P_V = F_V \cdot V_g \tag{5}$$

Where:

P_v– especific virtual power, W/m^3

Starting from equations (4) and (5) is obtained

$$F_V = \rho_s \cdot g \cdot \frac{V_f}{V_g} \cdot \cos^2\delta \tag{6}$$

The sum of equations (1) and (2) provides:

$$\rho_g \frac{dV_g}{dt} + \rho_s \frac{dV_S}{dt} = -\frac{dp}{dx} - \frac{\lambda_G}{D} \cdot \frac{\rho_g}{2} \cdot V_g{}^2 - \rho_g \cdot g \cdot sen\delta - \tag{7}$$
$$-\rho_s \cdot g \cdot sen\delta - F_V - Fsp$$

The friction force can be expressed with the aid of the friction coefficient

$$Fsp = \frac{\lambda z^*}{D} \cdot \frac{1}{2} \cdot \rho_s \cdot V_S{}^2 \tag{8}$$

According to Matousek [10] the total friction coefficient in the pipe surface is compound for a mechanical friction (contact between the particles layers and the wall of the pipe) and a viscous friction produced by the contact of the fluid with the walls of the tube. The friction coefficient λ_z^* depends on the material type and the characteristics of the rough surface. Different investigations have demonstrated that the wall ruggedness has a considerable effect in the particles collisions process with the wall [18]. According to Clyde Materials Handling [3] for lateritic pneumatic conveying system the coefficient is:

$$\lambda_Z{}^* = 0{,}325$$

Then the equation (8) takes the following form:

$$Fsp = \frac{0{,}1625}{D} \cdot \rho_s \cdot V_S^{\ 2} \tag{9}$$

Substituting the equations (8) and (9) in the forces general balance of the equation (7) is obtained:

$$\rho_g \frac{dV_g}{dt} + \rho_S \frac{dV_S}{dt} = -\frac{dp}{dx} - \frac{\lambda_G}{D} \cdot \frac{\rho_g}{2} \cdot V_g^{\ 2} - \rho_g \cdot g \cdot sen\delta - \\ -\rho_S \cdot g \cdot sen\delta - \rho_S \cdot g \cdot \frac{V_f}{V_g} \cdot \cos^2\delta - \frac{0{,}1625}{D} \cdot \rho_S \cdot V_S^{\ 2} \tag{10}$$

If the left side of equation (10) is developed, the total derivatives are:

$$\frac{dV_g}{dt} = \frac{\partial V_g}{\partial t} + V_g \frac{\partial V_g}{\partial x} \tag{11}$$

$$\frac{dV_S}{dt} = \frac{\partial V_S}{\partial t} + V_S \frac{\partial V_S}{\partial x} \tag{12}$$

In a stationary flow the partial derivatives with respect to time vanish, for it.

$V_g = V_g(X)$ y $V_S = V_S(X)$, then:

$$\frac{dV_g}{dt} = V_g \frac{dV_g}{dx} \tag{13}$$

$$\frac{dV_S}{dt} = V_S \frac{dV_S}{dx} \tag{14}$$

On the other hand, in the steady state the mass balance for the gas in the tube with a constant cross-sectional area is simply:

$$\rho_g \cdot V_g = const = m_g^{\ "} \tag{15}$$

where:

m_g"- mass flux, kg/s.m^2

And similarly the mass balance for the material flow is:

$$\rho_s \cdot V_S = const = \mu \cdot \rho_g \cdot V_g = \mu \cdot m_g^{\ "} \tag{16}$$

Substituting the equations (11 – 16) in (10) is obtained:

$$-\frac{dp}{dx} = \rho_g \cdot V_g \left[\frac{dV_g}{dx} + \mu \frac{dV_S}{dx} \right] + \frac{\lambda_G}{D} \cdot \frac{\rho_g}{2} \cdot V_g^{\ 2} + \rho_g \cdot g \cdot sen\delta \left[1 + \mu \frac{V_g}{V_S} \right] + \\ + \mu \cdot \rho_g \cdot \frac{V_g}{V_S} \left[g \cdot \frac{V_f}{V_g} \cdot \cos^2\delta + \frac{0{,}1625}{D} \cdot V_S^{\ 2} \right] \tag{17}$$

The relationship between the partial and real density of the gas is given by: $\rho_g = \varepsilon . \rho_G$.

The mass balance for the gas flow is $\rho_G . V_g$=constante. From this statement the following equation is obtained.

$$\rho_G \cdot \frac{dV_g}{dx} = -V_g \cdot \frac{d\rho_G}{dx} = -V_g \cdot \frac{d}{dx}\left(\frac{P \cdot M}{R \cdot T} \right) = -\frac{\rho_G}{P} \cdot V \cdot \frac{dP}{dx} \tag{18}$$

where:

P – gas pressure, Pa

M – gas molar mass, Moles

T – gas temperature, K

h – gas specific enthalpy, kJ/kg

ρ_G– real density; kg/m^3.

In the equation (18) is used the ideal gases and constant temperature so $\frac{dP}{dx} < 0$ and $\frac{dV_g}{dx} > 0$ in the length of the pipe.

The process of pneumatic conveying is considered isothermal h=h(T), the gas velocity is less than 30 m/s. For that in the equation (16) $T \cong Const$.

The solid velocity, V_s, also increase like a function of "x", and:

$$\frac{V_g - V_S}{V_{gA} - V_{SA}} = \sqrt{\frac{\rho_{GA}}{\rho_G}} = \sqrt{\frac{P_A}{P}} \tag{19}$$

Where

V_{gA}- gas velocity in the reference state, m/s

V_{SA}- solid velocity in the reference state, m/s

ρ_{GA}- gas real density in the reference state, kg/m^3

P_A- gas pressure in the reference state; Pa

For the calculation of the flotation velocity in any point of the pipe the following expression is applied

$$V_f = f(\rho_G) = V_{fA} \cdot \sqrt{\frac{\rho_{GA}}{\rho_G}} = V_{fA} \cdot \sqrt{\frac{P_A}{P}} \tag{20}$$

The reference state is considered to atmospheric pressure. If combine the equations (18) and (20) is obtained:

$$\frac{dV_S}{dx} = (-1/2) \cdot \frac{(V_g + V_S)}{P} \frac{dP}{dx} \tag{21}$$

In the equation (17) works with the partial density of the gas ρ_g and the solid ρ_s respectively, for a better development of the equation is necessary to introduce the porosity concept of the two-phase mixture that is defined for the following expression:

$$\varepsilon = \frac{\rho_g}{\rho_G} \tag{22}$$

In a similar way for the solid can think about the following expression:

$$(1 - \varepsilon) = \frac{\rho_s}{\rho_S} \tag{23}$$

The continuity equation for the particles and the air respectively is:

for the particles:

$$M_S = A \cdot V_S \cdot (1 - \varepsilon) \cdot \rho_S \tag{24}$$

For the air:

$$M_g = A \cdot V_g \cdot \varepsilon \cdot \rho_G \tag{25}$$

Where:

A – cross sectional area, m^2.

The mixture ratio is obtained dividing the equations (24) and (25).

$$\mu = \frac{M_s}{M_g} = \frac{V_S \cdot (1 - \varepsilon) \cdot \rho_S}{V_g \cdot \varepsilon \cdot \rho_G} \tag{26}$$

Substituting the equations (18 - 26) in the equation (17) is obtained:

$$\left[-1 + \frac{\varepsilon \cdot \rho_G \cdot V_g^{\ 2}}{P} + \frac{1}{2} \cdot \varepsilon \cdot \rho_G \cdot \mu \cdot \frac{V_g \cdot (V_g + V_S)}{P} \right] \frac{dP}{dx} = \frac{\lambda_G}{D} \cdot \frac{\varepsilon \cdot \rho_G}{2} \cdot V_g^{\ 2} + \\ + \varepsilon \cdot \rho_G \cdot g \cdot sen\delta \cdot \left(1 + \mu \cdot \frac{V_g}{V_S} \right) + \mu \cdot \varepsilon \cdot \rho_G \cdot \frac{V_g}{V_S} \cdot \left(g \cdot \frac{V_f}{V_g} \cdot \cos^2\delta + \frac{0{,}1625}{D} \cdot V_S^{\ 2} \right) \tag{27}$$

In horizontal pipes senδ=0 and cosδ=1, the equation (27) is reduced to the following expression:

$$\left[-1+\frac{\varepsilon\cdot\rho_G\cdot V_g^{\ 2}}{P}+\frac{1}{2}\cdot\varepsilon\cdot\rho_G\cdot\mu\cdot\frac{V_g\cdot\left(V_g+V_S\right)}{P}\right]\frac{dP}{dx}= \qquad (28)$$

$$\frac{\lambda_G}{D}\cdot\frac{\varepsilon\cdot\rho_G}{2}\cdot V_g^{\ 2}+\mu\cdot\varepsilon\cdot\rho_G\cdot\frac{V_g}{V_S}\cdot\left(g\cdot\frac{V_f}{V_g}+\frac{0{,}1625}{D}\cdot V_S^{\ 2}\right)$$

In vertical pipes senδ=1 and cosδ=0, the following expression is obtained:

$$\left[-1+\frac{\varepsilon\cdot\rho_G\cdot V_g^{\ 2}}{P}+\frac{1}{2}\cdot\varepsilon\cdot\rho_G\cdot\mu\cdot\frac{V_g\cdot\left(V_g+V_S\right)}{P}\right]\frac{dP}{dx}=\frac{\lambda_G\cdot\varepsilon\cdot\rho_G\cdot V_g^{\ 2}}{2\cdot D}+ \qquad (29)$$

$$+\varepsilon\cdot\rho_G\cdot g\cdot\left(1+\mu\cdot\frac{V_g}{V_S}\right)+\mu\cdot\varepsilon\cdot\rho_G\cdot\frac{V_g}{V_S}\cdot\frac{0{,}1625}{D}\cdot V_S^{\ 2}$$

The expression (27) constitutes the final equation of the theoretical model for calculation the pressure losses in lateritic mineral pneumatic conveying. Is necessary the identification of two parameters: the solid and flotation velocity of the particles. One and another constitute a function of the pipe length, equations (19) and (20). The simplifications of these expressions in horizontal and vertical line are in the equations (28) and (29).

III. Procedure for Mathematical Model Solution

In the solution of the differential equations (27, 28 and 29), that describes the theoretical model of lateritic mineral pneumatic conveying, is necessary to adjust the characteristic parameters of each material investigated starting from the experimental results, these are: flotation velocity and lateritic mineral velocity.

When establishing the lateritic mineral velocity with the employment of the model the term relative velocity is defined as the difference between the gas and solid velocity (V_g-V_S), this is obtained by means of the adjustment from the model to the experimental results. The method used to solve the differential equations of the theoretical model and to determine the relative velocity between the gas and solid is Runge - Kutta fourth order. The equations of the model are expressed in the form:

$$-\frac{dp}{dx}=f\left(V_{gX};V_{SX};V_{fX};\rho_{GX}\right)$$

And the derivative is calculated at each point using the previous known values for V_g, V_S, V_f, P.

The pressure loss produces an increment of gas velocity and the variation of other parameters as: density, flotation and solid velocity. To consider the variation of the parameters with the pressure the following equations are used:

$$V_{fX}=V_{fA}\cdot\sqrt{\frac{P_A}{P_X}} \qquad (30)$$

$$V_{gX}-V_{SX}=\left(V_{gA}-V_{SA}\right)\cdot\sqrt{\frac{P_A}{P_X}} \qquad (31)$$

Where the subscripts “A” represents the reference state to atmospheric pressure and “x” refers to the value of the parameters in any point of the system.

IV. Model Identification Algorithm

The task of mathematical model identification consists on the determination of the characteristic parameters of the lateritic mineral (flotation velocity V_F, and relative velocity between the gas and solid (V_g-V_S); for those the adaptation of the model that describes the process is guaranteed. With the result is necessary to compare the values of the characteristics of the real technological process:

$$\left[\left(\frac{dp}{dx}\right)_{\exp}\right]$$

With the magnitudes Y_M to the exit of the object for the equations (28 and 29). Is better that combination of parameters where:

$$\left[Y_O-Y_M\right]\rightarrow\min \qquad (32)$$

In the model identification is necessary to use an iterative procedure starting from the reference state, and the Runge - Kutta fourth order method that takes into account the behavior of the one derived in four points of each interval. This method, like part of the iterative process is used to solve the theoretical model and to find the values of the characteristic parameters in the laterític mineral (flotation velocity and relative velocity between the gas and the solid).

The confirmation of the validity of experimental values with the theoretical model is developed through the relative error, that is to say, the difference among the module of the experimental value “Xexp” of the pressure fall and the theoretical value “Xteo” obtained from the model for the same conditions of the experiment.

The relative error for each point is calculated by the following expression:

$$E_p=\left|\frac{X_{\exp}-X_{teo}}{X_{\exp}}\right|\cdot 100 \qquad (33)$$

The average relative error is expressed for:

$$E=\sum_{i=1}^{n}\left|\frac{X_{\exp}-X_{teo}}{X_{\exp}}\right|\cdot\frac{100}{n} \qquad (34)$$

V. Results and Discussion

Determination of the model parameters

In table 1 the results of flotation and relative velocity are exposed for each one of particles diameters. The flotation velocity was determined experimentally in [20]; the relative velocity is determined by adjustment of the model.

Table 1. Relative and flotation velocity values for different diameters of particles.

	Horizontal pipe			Vertical pipe		
dx (mm)	V_{gA}-V_{SA} (m/s)	Vf_A (m/s)	E (%)	V_{gA}-V_{SA} (m/s)	Vf_A (m/s)	E (%)
0,250	4,27	5,21	7,84	2,32	5,21	7,10
0,1875	3,6	4,74	8,02	1,97	4,74	8,53
0,1075	3,39	3,83	9,31	1,51	3,83	10,07
Mezcla	5,18	5,21	9,54	2,74	5,21	7,04

The values of the relative error confirm the validity of the obtained results, their magnitude doesn't overcome 10,07 %. Judging by the behavior of the results (table 1), as much the relative velocity as the flotation velocity for both cases depend on the size of the mineral particle (R^2 overcomes 0,987). It is interesting that the type of dependence of the relative velocity for both cases is different, in the case of horizontal pipes the dependence of the mineral particle size is polynomial of second grade; for vertical pipes the dependence is lineal.

Behavior of the pressure loss in function of the gas velocity for horizontal and vertical pipes.

The behavior of pressure loss is obtained by means of the model parameters (table 1), in pipes with a diameter of 100 mm varying the mass flow in three levels (3600, 5520 and 7200 kg/h).

The figure 2 shows the dependence of the pressure losses in function of gas velocity for different solid mass flows. With the increment of the gas velocity, until near values to the 5,21 m/s, decrease the pressure losses that defines the transport in discontinuous dense phase. In the region of minimum pressure loss, the drop of gas velocity causes a fast increment of the solid concentration. The point where the gas cannot drag the material, this is deposited in the bottom of the pipe. This phenomenon is known as "saltation transports" and is identified by fluctuations of the pressure loss.

For values of the gas velocity superiors to 6,12 m/s the transport is made in continuous dense phase and belongs with the area of rational transport for the Cuban lateritic mineral where the smallest losses of pressure take place.

The dependence of the pressure loss of gas velocity in horizontal pipes shows differences with the transport in vertical pipes (figures 3). The reduction of pressure takes place until values of gas velocity next to 4 m/s.

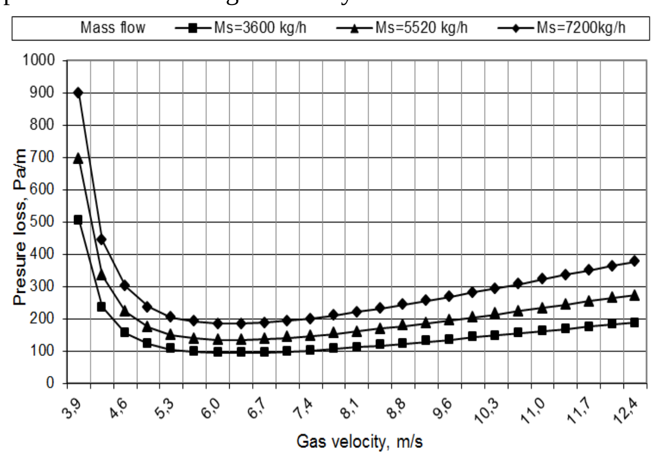

Fig. 2. Behavior of the pressure loss in function of the gas velocity in horizontal pipes and dx = mixes of material

Similar to the transport in horizontal pipes (figures 3), in the mineral transport in vertical pipes a region of minimum pressure exists when the change is located between the dense and fluid phase. This phenomenon is known as "choking" and the choking velocity is defined as the lowest velocity at which the dilute phase transport can be operate. The discontinuous dense phase extends in the intervals of gas velocity from 4 m/s to 5,21 m/s, starting from this last value and until the 18 m/s, the continuous dense phase is developed.

In accordance with the results obtained for a pipe diameter of 100 mm and a solid flow constant, the choking velocity is always smaller than the saltation velocity in horizontal pipes; also in the pneumatic conveying systems the change velocity can be selected starting from the saltation point, that is to say the most critical values among the horizontal and vertical transport.

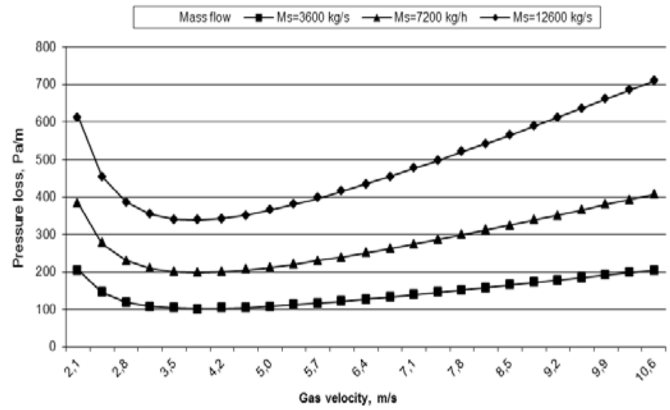

Fig. 3. Behavior of the pressure loss in function of the gas velocity in vertical pipes and dx = mixes of material.

The pressure losses in the vertical transport are bigger than the horizontal one, this behavior in the lateritic mineral is exposed in the figure 4. The pressure quotient among both systems is between 1.1 and 1.45. The biggest values in the quotient are in the region between the dense and fluid phase; also is observed an increment of the same one with the increase of the mass flow of transported material.

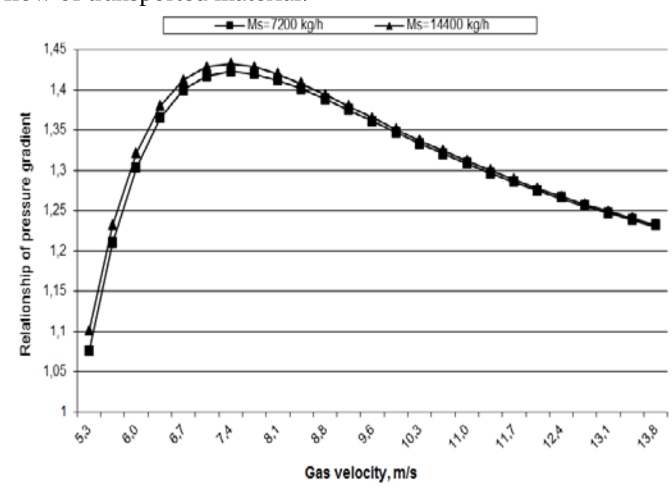

Fig. 4. Behavior of (dp/dx)vertical/(dp/dx)horizontal in function of the gas velocity

VI. Conclusions

- The theoretical-empiric model of lateritic mineral pneumatic conveying is formed by three differential equations (27, 28 and 29) that describe the behavior of the process, being also included several connection equations. It is identified by means of an algorithm that allows the comparison of experimental and the model results.
- The relative velocity between the gas and the solid in horizontal and vertical pipes is inferior to 5,18 m/s. The flotation velocity has a maximum value of 5,21 m/s. The values of relative error confirm the validity of the obtained results, the magnitude doesn't

overcome 10,07 %.

- The lateritic mineral pneumatic conveying is carried out in discontinuous dense phase in inferior zone to 6,12 m/s into horizontal transport and 5,21 m/s in vertical one. The transport zone in continuous dense phase extends until 18 m/s in both cases.

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