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REGIME MIXING RATIO IN VACUUM DILUTE PHASE PNEUMATIC CONVEYING SYSTEMS

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Abstract: This paper analyses some aspects of regime mixing ratio (RMR) in Vacuum Dilute Phase Pneumatic Conveying Systems in order to measure the energy efficiency of these systems. RMR variation curve profile is determined and the proportionality between Theoretical Mixing Ratio (TMR) and RMR is evaluated. The equation of the Characteristic Curve of the Ventilator type APRG-902/C is given. The profile of the RMR variation curve by specific load of the pipe is determined.

Keywords: pneumatic conveying, dilute phase, regime mixing ratio

Introduction

Within the modern cereals grinding plant, the pneumatic conveying has become an indispensable element due to the fact that the benefits they bring outweigh those of the mechanical transport. Sizing pneumatic transport systems within the cereals grinding departments is made on the basis of recommendations from the literature or based on experience gained by specialized companies or professionals. The purpose of this paper is to discuss some aspects of regime mixing ratio which ultimately condition the energy consumed by a Dilute Phase in Vacuum Pneumatic Conveying System and gives a measure of the energy efficiency of these systems.

Current stage

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Currently, the calculation of Pneumatic Conveying Systems operating in Vacuum in the Dilute Phase (shortly DPIVPCS), starts from some recommendations of the specialty literature regarding the values of the theoretical mixing ratio (Gerecke, 1991), (Meissner, 2008), (Costin, 1983) . The recommended values are based on the experience accumulated in this field by the profile companies or by the professionals in the field of pneumatic conveying. As a result, the pneumatic conveying systems have different configurations according to each supplier and what differentiates them is the specific consumption of electricity (kwh/tone of conveyed product).

Progresses and innovations

The first researches in the vacuum pneumatic conveying in dilute phase were performed in 1923 by Gasterstadt who put the bases of the calculation mode (Klinzing, 2009). After 1950s, two researchers (W. Barth and Segler), based on the experimental determinations (Bulat, 1962), (Klinzing, Rizk, Marcus, Leung, 2010), have proposed an assessment formula for the correlation between:

- The Clogging Regime Mixing Ratio (CRMR)
- The conditions of process dynamics, in this case Froude criterion
- A Constant C of the product

The proposed formula is:

$$\mu_{cr} = C * Fr^{2} \quad (1)$$

where:

- μ_{cr} is the Clogging Regime Mixing Ratio (CRMR), in [kg product/kg air]
- C is the Clogging Constant of the Product, that for the homogeneity of the formulae have to have the same units as mixing ratio
- Froude criterion, dimensionless

Following the experimental determinations (Tanase, 2012), the necessity of dimensional and accuracy correlation was highlighted for this constant. Therefore, for the equation expressing the variation of the CRMR, according to the dynamics of the process and the product's clogging constant, the following formulation was proposed:

$$\mu_{cr} = C * S_c * Fr^{2} \quad (2)$$

where:

- S_c is the cross section area of the conveying pipe, in [m^2]

- C is the Clogging Constant of the Product, expressed as [kgproduct/kgair/m^{2}ofcross section area of the pipe], (Tanase, 2012)

Regime Mixing Ratio (RMR)

In pneumatic conveying, the reality of the phenomenon is that the product always remains lags compared to the air flow and this fact has to be considered. This arrearage is proportional to the difference between the air speed and the floating speed of the particles within the respective mixture, the floating speed given by the respective conditions of product flow rate and the pipe diameter. In fact, the difference between the air speed and the speed of the product shall always be the floating speed (the floating speed given by the value of the product concentration, i.e. the flow rate to be transported and the pipe's diameter) (Bulat, 1962), (Klinzing et. al., 2010). The fact that the product lags leads to the increase of the mixing ratio value, initially estimated as "theoretical" (TMR - Theoretical Mixing Ratio). By the definition relationships of RMR (Regime Mixing Ratio) and TMR, it results:

$$\mu_{cr} = \mu_t * \frac{v_a}{v_p} \qquad (3)$$

where:

- μ_r is the Regime Mixing Ratio (RMR), in [kgofproduct/kgofair]
- μ_t is the Theoretical Mixing Ratio (TMR), in [kgofproduct/kgofair]
- v_a is the speed of the air, in [m/s]
- v_p is the speed of the product, in [m/s]

In practice, it is immediately acknowledged that together with the TMR increase, there takes place the decrease of the speed of the product and, implicitly, the RMR value increases somehow proportionally with the theoretical mixture ratio variation. The determination of this proportionality represents one of the subjects of the present study. From those mentioned up to now, it results that the order relationship between the mixing ratios is the following:

$$\mu_t < \mu_r < \mu_{cr} \qquad (4)$$

where:

- μ_t is the theoretical mixing ratio, i.e. TMR, [kg product/kg air]
- μ_r is the regime mixing ratio, i.e. RMR, [kg product/kg air]

- μ_{cr} is the clogging regime mixing ratio, i.e. CRMR, in [kg product/kg air], defined according to the relationship (2)

The necessity to evaluate the proportionality between TMR and RMR

When calculating a DPIVPCS, it starts from a given value for the TMR and of those known so far, we can estimate the value of CRMR (the limit of the system), (Tanase, 2012). But there is a risk to calculate a pneumatic conveying system such a manner that, although TMR is less than CRMR and theoretically the system should be functional, in reality the system cannot work because RMR reaches CRMR value and clog the system before it reaches the proper loading of TMR scheme. For this reason, the relationship must be assessed on order condition (4). From the things known up to now, we have (or we can estimate) TMR and CRMR. By assessing RMR understand establish a procedure by which it can be estimated with a satisfactory accuracy, its value. Due to the fact that RMR is closely linked to the value of TMR, according to (3), it is necessary to evaluate the variation of RMR according to TMR. Using the information existing from the experimental determinations (Tanase, 2012), we represented graphically the RMR variation compared to the Specific Load of the pipe (Figure 1).

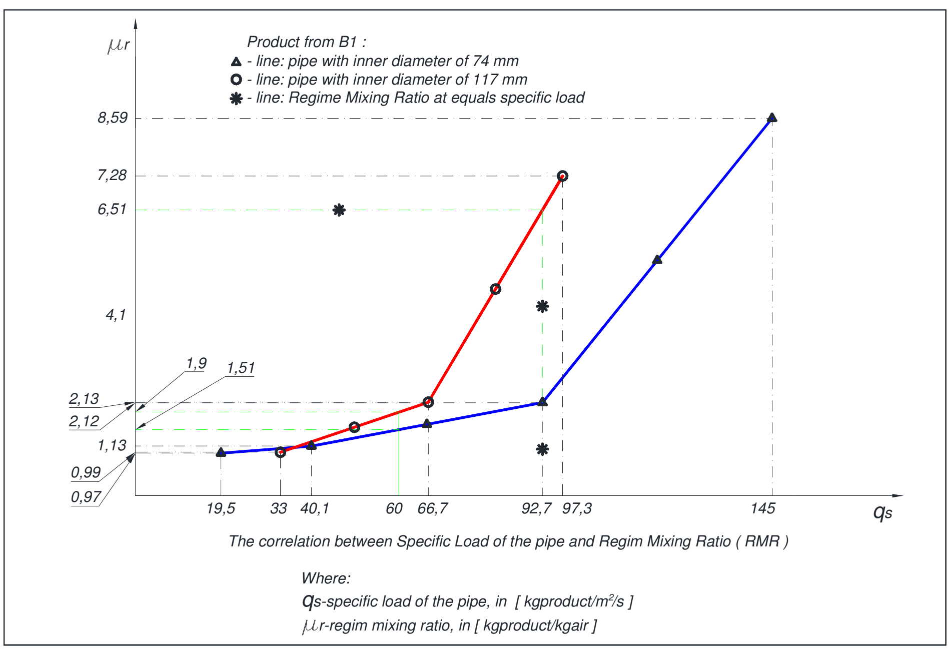

Figure 1: RMR variation according to the Specific Load of the Pipe

The segments resulted by the association of the points show that the function has somehow a profile of an exponential function. In order to have an assessment procedure for the conditions of performing the pneumatic conveyinge, it is absolutely necessary to determine the profile of the RMR assessment curve, according to the Specific Load q_s of the pipe.

Assesment of the RMR

Determination of the RMR variation curve profile

Before proceeding in the determination of the variation curve profile, some additional comments have to be done and supplementary conditions have to be established. The determination of the regime mixing ratio value is a very difficult task. The number of variables implied is very high and an accurate determination of it is practically impossible. Nevertheless, in order to assess the manner in which RMR is influenced by the pipe loading degree, the following reasons and simplifying hypotheses were considered:

- The development of product cloud, the intimate mixture of product and air, takes place in the acceleration area of the pneumatic conveying pipe;
- Once the product cloud is formed at the end of the acceleration area, it precisely defines the regime mixing ratio RMR. Its value at the end of the acceleration zone shall remain constant on the entire piping disposition, namely it shall be found on the entire subsequent length of the pipe, leaving aside the variations given by the local/liniar and reaccelerating resistances;
- The entire "miracle" in DPIVPCS takes place within the acceleration zone**,** the rest of the pneumatic conveying pipe being practically irrelevant. That it is irrelevant because all the things taking place within the entire pneumatic conveying pipe, excepting the acceleration area, is described accurately enough by the equations of the pressure losses;
- Some variables were considered, such as the air density and the thermal and chemical potential functions of the system as being constant. For the DPIVPCS, the air speed does not exceed 1/3 of the air sound speed and we can consider the density as being constant;
- The length of the acceleration zone being generally very short (of maximum some meters for the granular/powdery products), related to the total pipe length, the pressure losses due to clean air on this portion could be considered as being null;
- In order to simplify the problem, it was considered that the exhaust fan is imaginary, introduced into the pipe, being placed exactly at the end of the acceleration zone (Figure 2);

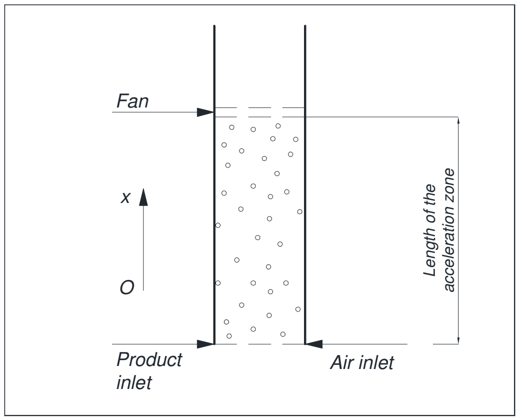

Figure 2: The acceleration zone and the location of the imaginary ventilator at the end of the acceleration zone

- The revolution speed of the ventilator is constant;
- As a result of the fact that the diameter of the pipe is not changed along the conveying route and to the fact that the air density is constant, the air speed within the pipe does not change;
- One of the operating curve of the ventilator was considered as having the profile presented in Figure 3. This curve is in fact the curve of the constant revolution speed of the ventilator. In the initial status with product flow rate equal to zero, the exhaust fan shall operate on one of the points of the curve, namely the Total Pressure P_1 and Flow rate L_1 . Their product, namely the surface area, gives us the power consumed by the ventilator under these circumstances of flow rate and pressure. The curve presented in Figure 3 is not a hypothetical curve, but is a general curve of a pneumatic conveying fan, inspired from the curves made available by the ventilators designers and manufacturers (Euroventilatori, 2006).
- From those exposed above, we can say that the entire energy necessary for the pneumatic conveying is “consumed” from the static pressure generated by the ventilator. It behaves as a potential energy for the system
- The interface that makes converting pressure energy loss in static pressure is the dynamic pressure. In fact, the dynamic pressure is the one generating the pressure losses
- Because of the short length of the acceleration area, it was considered that the variation of the potential energy of the product is negligible
- It was also considered that the piping diameter behind the ventilator is equal to the piping diameter in front of the ventilator (Figure 2).

Taking into consideration these mentioned above, the question arises to find a relationship, an equation which describes the variation of the regime mixing ratio by the TMR. In fact, the more appropriate way to make this analysis is to evaluate the RMR variation by the specific load of the pipe. Before passing to the analysis of the phenomenon, the approach method is structured as follows:

- The assessment of Equation Curve of the Fan
- The Profile of RMR variation curve by the Specific Load of the pipe

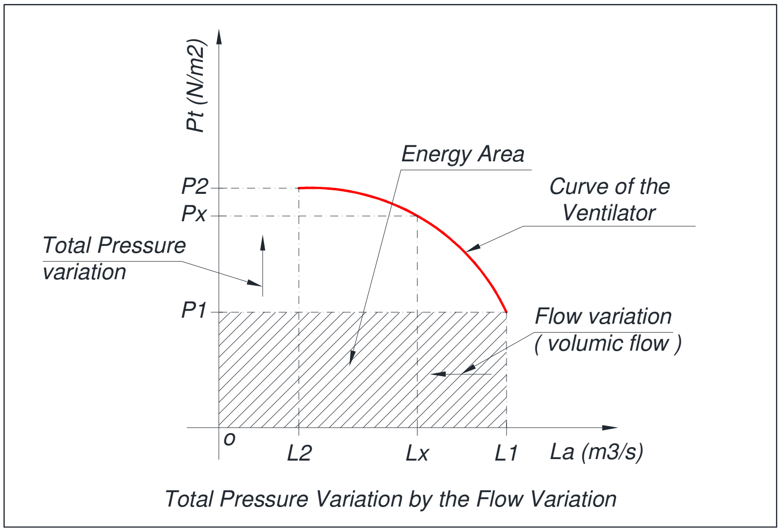

Figure 3: The operating curve of the ventilator at the initial conditions

Equation of the Characteristic Curve of the Ventilator

Analysis of variation of RMR curves requires an assessment of the Characteristic Curve of the Pneumatic Conveying Fan. These curves are provided by the manufacturers of fans and are specific to each type of fan. For a general pneumatic conveying ventilator, with a power between 30 and 90 [kw], the most common in the milling units, this curve has a profile similar to that shown in Figure 4 (for the regime "in aspiration"). This one is the characteristic curve of a fan type APRG-902/C power 75 [kW] (Euroventilatori, 2006), with a maximum volume flow rate of 4,67 [m^3/s] to which correspond a minimum total pressure of 1.110 [kgf/m^2], and a minimum volume flow rate of 1,67 [m^3/s] to which corresponds a maximum total pressure of about 1.610 [kgf/m^2]. Tolerances in the values of the graph are given by the manufacturer to (+/-) 5%. Fan characteristic curve has a parabolic arc profile for which the equation is not given.

According to Eck (2003), the variation of static pressure depends on the square of the variation of the air flow. This is also highlighted by some experimental tests conducted by some companies specialized in building fans (Grenhack, 2005), on the effectiveness of these machines and it is evident that there exists the slope of the parabola and there is a relationship described by the following equation:

$$P_s = k * L^2 \tag{5}$$

where:

- P_s is the Static Pressure corresponding to the flow L, in [Pa]
- k is the constant that reflects the slope of the parabola, dimensionless
- L is the air flow, in [m^3/s]

The equation is an empirical one and does not dimensional correlates the parameters. In DPIVPCS systems, air velocity does not exceed one third of the speed of sound in air and, therefore, we can assume that the air density is constant. In these conditions, the similarity with the pumps for liquids is obvious.

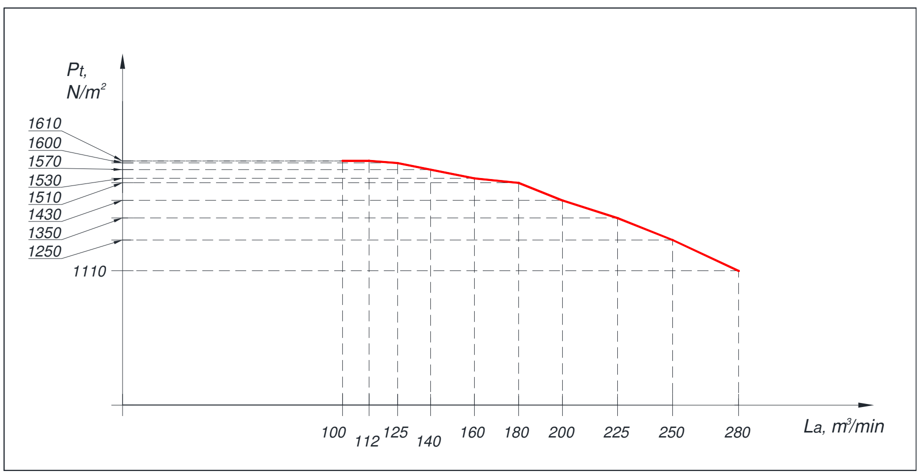

Figure 4: Characteristic Curve of fan type APRG-902/C

For the pumps for liquids, exists experimentally derived equations that are defining the Characteristic Curve of these pumps. One of these (LMNO Engineering, Research and Software Ltd., 2013) , deduced based on Hazen-Williams equations has the following form:

$$H_x = H_{max} * \left(1 - \frac{Q_x^2}{Q_{max}^2}\right) \tag{6}$$

where:
- H_x is the pressure corresponding to the flow Q_x, in [N/m^2]
- H_{max} is the maximum pressure corresponding to zero flow, in [N/m^2]
- Q_x is the volumic flow at which the pumps works, in [m^3/s]
- Q_{max} is the maximum volumic flow at zero pressure, in [m^3/s]

Opposite the characteristic curve of a fan, for different values of air volume flow contained between (L_{min}, L_{max}) of the Figure 3, the equation (6) does not produce values consistent with the pressures resulting from the chart representing the curve of that pneumatic conveying fan (Figure 4).

By analyzing the graph in Figure 4, we can estimate that the arc of the graph in this figure is a part of the graph of an ellipse. Writing the equation of an ellipse, results the following form of the equation of the curve:

$$y = \pm \frac{b}{a} * \sqrt{a^2 - x^2} \tag{7}$$

Replacing with proper notations for flow and pressure and introducing into the equation a constant for the fan, the following form of the equation follows:

$$P_x = P_{max} * \sqrt{1 - k_v * \frac{L_x^2}{L_{max}^2}} \tag{8}$$

where:
- P_x is the total pressure corresponding to the flow L_x, in [N/m^2]
- P_{max} is the total maximum pressure that can be achieved by the fan at zero rate of flow, that is the intersection of the ellipse with the ordinate, in [N/m^2]
- L_x is the air flow at which the fan operates, in [m^3/s]
- L_{max} is the maximum air flow fan that can be achieved by the fan determined at the intersection of ellipse with abscissa in [m^3/s]
- K_v is a constant of the fan that depends on the difference between the P_{max} and P_{min} and gives the slope of the curve, dimensionless

The analysis of the equation (8) indicates:
- the argument of the radical function must be a positive number. The function represented by this equation is not differentiable on the interval ends (L_{min} , L_{max}), but is differentiable on this interval
- the constant k_v is a specific one to each fan unit or range of fans

- Maximum value L_{max} of the flow is actually the maximum volume flow at a zero total pressure and represents the point of intersection of the parabola with the abscissa. Can have only positive values.

In terms expressed herein above by assigning values of the constants in equation (7) and (8) and assuming according to equation (7) and (8) that “b” represents the pressure and “a” represents the flow as follows: b=1670, a= 395 and k_v = 1,11 , for values of L_x in the domain (L_{min}, L_{max}), the values obtained for the function P_x and represented in the Figure 5, are according to the values of the total pressure from Figure 4. Thus, equation (8) describes, with maximum deviation of 1-2%, the values of the total pressure represented in Figure 5, deviations that are within the tolerances given by the manufacturer measurements within +/- 5% (Figure 4).

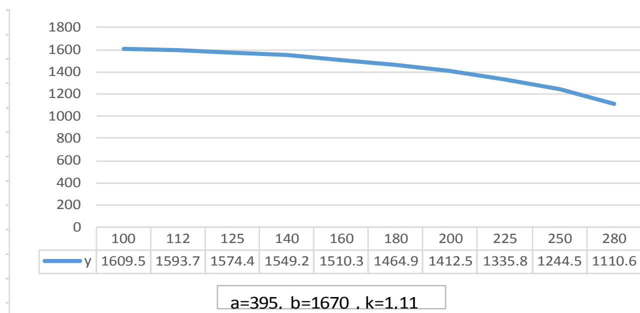

Figure 5: Characteristic Curve of the fan type APRG-902/C, plotted with eq. (8)

Value of 1670 of the constant “b” is the value of the total pressure obtained at the intersection of the ellipse with vertical axis, the ordinate, and the value of 395 for the constant “a” is the volume flow value obtained at the point of intersection of the ellipse with the horizontal axis of abscissa.

The profile of the RMR variation curve by Specific load of the pipe

The profile of the characteristic curve in Figure 1 is determined in this paragraph. Analyzing the graph in the Figure 1, can be noticed:

- The variation is continuous, i.e. the definition range is from zero (excluding zero) to the maximum value (excluding the maximum value) corresponding to the clogging regime value;
- The specific load variation can be in steps ever so short. Of course, the lowest increment value shall be given by the mass value of the smallest particle within the product flow;
- The function in case, i.e. RMR, is a continuous specific load function.

The question arises whether to determine if the variation curve, the function graph given by the equation (3), describes a convex or concave curve. We shall evaluate the second derivative of the function. In order to be able to derivate the equation, we shall write the equation (3) according to the specific load of the pipe:

$$\mu_r = \frac{1}{\rho} * \frac{q_s}{v_p} \quad (9)$$

where:

- μ_r is the Regime Mixing Ratio, i.e. RMR, [kg product/kg air]
- ρ is the air density, [kg/m^3]
- q_s is the Specific Load of the pipe, [kg product/ m^2/s)]
- v_p is the speed of the product, [m/s]

In the form the equation (9) presents, it is difficult enough to be derived, because the speed of the product depends also by the specific load. As discussed above, we are interested only in the sense the equation gets after derivation. In the expression given by the equation (9), we shall replace the value of the speed of the product by its expression of the kinetic energy, and the mass shall be expressed according to the specific load. In the following, although the kinetic energy is a form of assessment of mechanical work, because the mass of the product is expressed as mass flow of product [kg/s], I will allow to refer to it as a power consumption for accelerating the amount of product that can be found in the volume of the acceleration zone and therefore appears expressed in [w]. We shall obtain the following expression for the speed of the product:

$$v_p = \sqrt{\frac{2 * E_c}{q_s * S_c}} \quad (10)$$

where:

- E_c is the kinetic energy of the product quantity within the volume of the acceleration zone, [w]
- q_s is the Specific Load of the pipe, [kg product/m^2/s]

- S_c is the pipe section area, [m^2]
- v_p is the speed of the product at the end of the acceleration zone, [m/s]

As it results from the equation (10), the kinetic energy has the expression of a power and it actually represents the power consumed with the mass m_{px} of product in the acceleration zone. Because the kinetic energy can have only positive values, i.e. it can increase or decrease but will always be positive, considering the positive direction O-x (Figure 2), for the calculation of the limit of the equation (9) we shall consider the Kinetic Energy as being constant, deriving only in relation to the variable Specific Load i.e. q_s . Replacing the speed given by the equation (10) to the equation (9) and its derivation, we reach at the second degree derivate which has the following expression:

$$\frac{\partial^2 \mu_r}{\partial q_s^2} = \frac{3}{4} * \frac{1}{\rho * \sqrt{\frac{2 * E_c}{S_c}}} * \frac{1}{\sqrt{q_s}} \qquad (11)$$

Analyzing the equation (11), we can notice that it can gives only positive values and the graphical representation of RMR variation according to the specific load of the pipe can be only a convex curve (Figure 6).

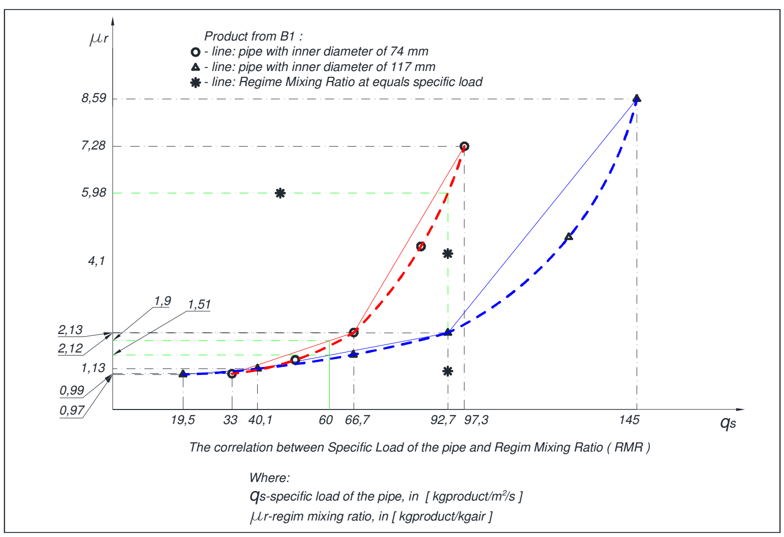

Figure 6: Variation of the RMR by the Specific Load is a convex curve

CONCLUSIONS

The value of the regime mixing ratio is always acc. to the eq. (4)
For a correct designed pneumatic conveying system the value of RMR have to be enough lower than the CRMR for to prevent also some variations in system balance due to the variation of the parameters of the air flow. Some variations of the product mass flow could also occur.
The variation of the regime mixing ratio (RMR) is influenced by the performance of the pneumatic conveying fan used
The equation (8) describes enough accurate the profile of the curve of the pneumatic conveying fan
The profile of the variation curve of RMR is a convex one
The ratio between RMR and CRMR influence the energy efficiency of the Dilute Phase In Vacuum Pneumatic Conveying Systems
A procedure for to predicting RMR from designing phase is necessary

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