ENERGY EFFICIENCY of VACUUM PNEUMATIC CONVEYING IN FLOUR MILLING – LIMIT CONDITION

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Abstract: Energy efficiency of vacuum pneumatic conveying systems in a flour mill, assessed as [kw/to of product] processed by the given plant, is a permanent and present issue among the millers. One should define this power consumption of pneumatic system, reported to B1 capacity of the plant, as Specific Consumption of Pneumatic Conveying System. Rather than being just a new parameter, as we will see further, due to the uncertainty regarding the limits of these type of systems, there is still large gap for optimization for this transport solution for the intermediate stocks and this could have a major impact on the general specific consumption of the plant and on the production cost for the flour. By the present paper we revue the existing situation and the recent achievements and progresses in maximizing the efficiency of such plants, i.e. lowering the specific consumption of the Vacuum Pneumatic Conveying Systems in the flour mills.

Key words: pneumatic conveying, energetic efficiency, optimising pneumatic conveying

1. Introduction.

The necessity of pneumatic conveying in transporting the intermediate stocks in flour milling is an undoubted fact among the millers. The advantages of this systems as simplicity, stability, lower maintenance cost and many other advantages of this solution, are making it, by far, the preferred conveying solution in the grinding section. A standard configuration for such a system involves some well known parts as: receiver or injector, transporting pipe, separating element for the air and the product such as the cyclones, closing and unloading device such as air-lock, separation filter and of course the ventilator (fig. 1).

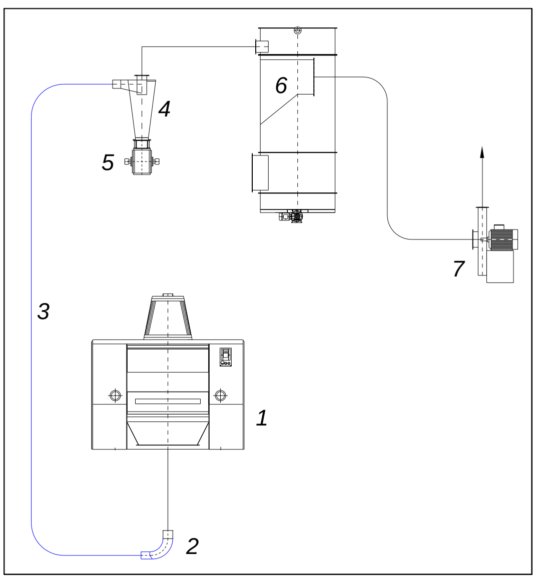

Fig. 1: General configuration of a vacuum pneumatic conveying system: 1-rollermill, 2-injector, 3-conveying pipe, 4-cyclone, 5-air-lock, 6-filter, 7-high pressure fan

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2. Designing Procedures.

2.1. Present approach.

The procedure for designing this system is well known for the specialized engineers. The main scope of this is to identify the fan that is most suitable for that given application. It implies some initial conditions as for the type of product to be transported, the capacity, the configuration of the line and some other location factors such as the average temperature of the geographic area, the altitude, etc. From the specialized literature we can have the mixing ratio for that given product and using some equations we are calculating the pressure loss on that line. Applying some corrections for the air density variation and some air flow loses, we find by this procedure the ventilator. The main inconvenient of this procedure is that it not gives us any hint about the real necessary consumption for to lift the product, but only solves the problem in a questionable manner at least in terms of energy consumption.

2.2. Our approach.

Before starting to discuss a more energy efficient way for the pneumatic conveying in grinding section, we should analyse what is really happening during the vacuum pneumatic conveying in each of the components of the system.

2.2.1. The ventilator.

Even if it is the last machine involved in the pneumatic system it is for sure the most important one. In a vacuum pneumatic conveying system in a flourmill, almost the entire electric power is consumed by the fan. After all, our entire work in this presentation is focused on finding solution for to optimise the system and mainly the fan.The performance of a fan is in general given by its characteristics curve (fig.2)

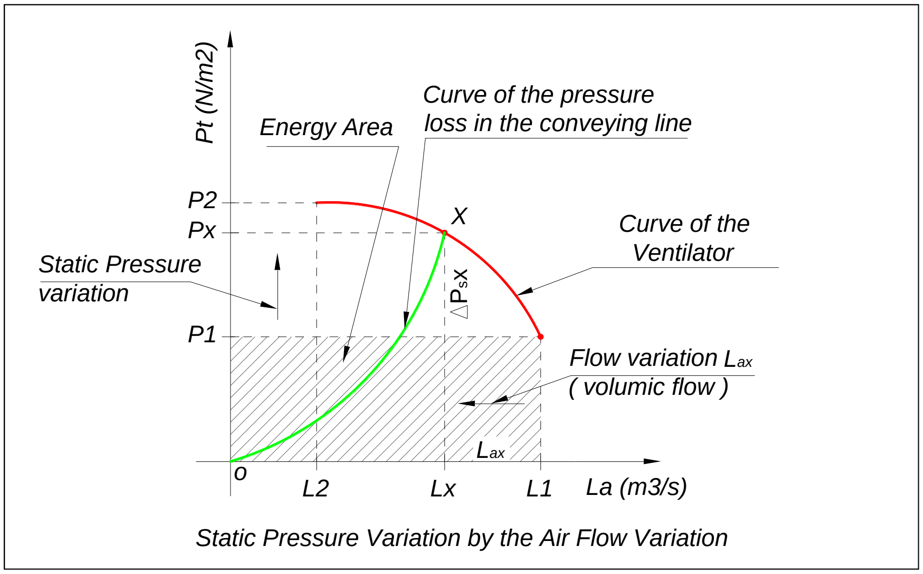

Fig. 2: The Characteristic Curve of a fan

For a start condition, let say empty pipe, the fan will be on the initial position, denoted as flow L_1 and the pressure P_1. The total energy (theoretical) consumed by the fan at this point, is equal to the area of the rectangle. Loading the system with product, will require from the fan to add additional pressure. And this is made by decreasing the air flow up to the point L_X and consequently the dynamic pressure, while increasing the static pressure up to the corresponding point P_X (conversion of dynamic pressure into static pressure). The energy consumed by the fan at this working regime is again the area of the corresponding rectangle and, as it can be seen from practical measurements, is lower than the initial position. The working point is the intersection point between the system resistance and the curve of the ventilator.

Analysing the graph, we can see that there are some strong connections between the loading regime of the pipe, the resistance the air and product mixture flow generates in the pipe, known as system resistance, and the profile of the curve of the fan. The slope of the curve of the ventilator, at a certain point, is the one that dictates the displacement of the flow and pressure from that certain point to a new equilibrium point. If more flat profile curves fan are used, than a higher displacement should be expected for the air flow amount, that is lowering, and this, at a certain moment, becomes dangerous for the system, approaching the clogging regime of some pipes. One more mention about the fan: given the working mode described by the curve of the fan, the energy yield of the fan is decreasing when loading the plant with product. As any miller knows, the normal state of a flour mill is to operates continuously at a constant regime, since any under loading conditions increase the specific consumption of the fans.

2.2.2. Product receiver or the injector.

The product enter the system through that receiver or injector. In many mills, there are used mostly two different type of injectors namely, horizontal and vertical. The larger part of the conveying air enters the system through the rollermill, ensuring in this way also the required aspiration of the machine. And all this air amount flows through the gravitational transporting pipe toward the injector and increases the velocity of the falling product. The product enter the receiver, has to reach the zero point of its vertical component of the velocity, actually its kinetic energy becomes zero, and needs to be accelerated and further transported in the line. The slip factor between the air and product becomes 1 at this point.

In contrast to this, in the horizontal injectors the product does not pass through this zero kinetic energy point. Being accelerated in the flowing pipe after the rollermill due to both air flow and gravity, the products enter the horizontal receiver that guides it into the pneumatic conveying pipe.

From an energy point of view it is clear that the vertical injector is the most inefficient one and the highest energy consumer among the other types of injectors, especially compared to the horizontal type. When calculating the pressure loss in the pipe, a big portion of the total pressure loss of the line is given by the pressure loss for to accelerate the product. Keeping a higher velocity of the product, helps in preserving the energy consumption of the line. To remark that the air entering the receiver, it reaches its first point transporting speed just at the very first cross section of the pipe. This speed is considered when making the calculations. The entire accelerating process for the air takes place outside of the receiver.

2.2.3. Transporting pipe.

In the present discussion we will not take into consideration the configuration of the line nor the length of it. These are giving only quantitative approach of the phenomenon, while we are interested in qualitative aspects of this. If the system succeeds in accomplish its task, i.e. to handle the transport, we should emphasize that the air speed when leaving the pipe is higher than the inlet point speed. And this is connected to the variation of the density of the air due to the static pressure existing along the conveying pipe. After entering the pipe, the mixture of air and product is accelerated towards the upper point, the cyclone. The interesting phenomenon is that the air is continuously accelerating up to the next point of cross section change, i.e. the inlet of the cyclone. Our tests shows that there is no such thing, as constant velocity in the pipe, neither for air nor for product. The pressure gradient generated by the ventilator, makes the air lowering the density and due to this the velocity of the air is continuously increasing, as long as the cross section and the shape of the pipe remains unchanged (eq. 1).

$$\vec{a} = -\frac{1}{\rho_0\left(1-\frac{\Delta P}{P_0}\right)}\overrightarrow{\nabla P} \quad (1)$$

Where:

$\vec{a}$ – average acceleration of the air flowing in the pipe, [m/s^2]

ρ_0 – standard air density in the considered location, [kg/m^3]

ΔP – pressure difference between the inlet point of the injector and inlet point of the cyclone, [kPa]

P_0 – standard air pressure in the considered location, [kPa]

$\overrightarrow{\nabla P}$ – pressure gradient in the considered line, [kPa/m]

Based on this, considering a pipe 20 m length, and estimating a pressure loss of 500 mmWC on the conveying line, we find out that for inlet speed of the air of 20 m/s, standard values for density and pressure, the final speed, when entering the cyclone, will be about 24 m/s.

If a line is under loaded with product it means that the static pressure, the pressure loss on this line, is lower. In the same time the low that govern the air flow says that the total pressure have to remain constant and due to this the system will self-balance such that the velocity of the air in this line increases while decreasing the static pressure and the result is that actually the air flow on this line increases. Since the total air flow generated in the system by the fan is constant, given a regime point X (see fig. 2), it means that air flow will increase in some under loaded lines to the detrimental of some over loaded lines, were the air flow will be decreased. The effect is cumulative as one unbalancing factor being the increasing of the product flow while on the same pipe the air flow is decreasing. For specific conditions, for a given flow, a type of product and a pipe diameter there is a certain amount of air that brings the system at pneumatic conveying regime. From the variation of the pressure in a fluidized bed, as shown in the fig. 3, it is obvious that exists a zone of maximum efficiency of the system, in terms of pressure and air flow, that means consumed power on the fan.

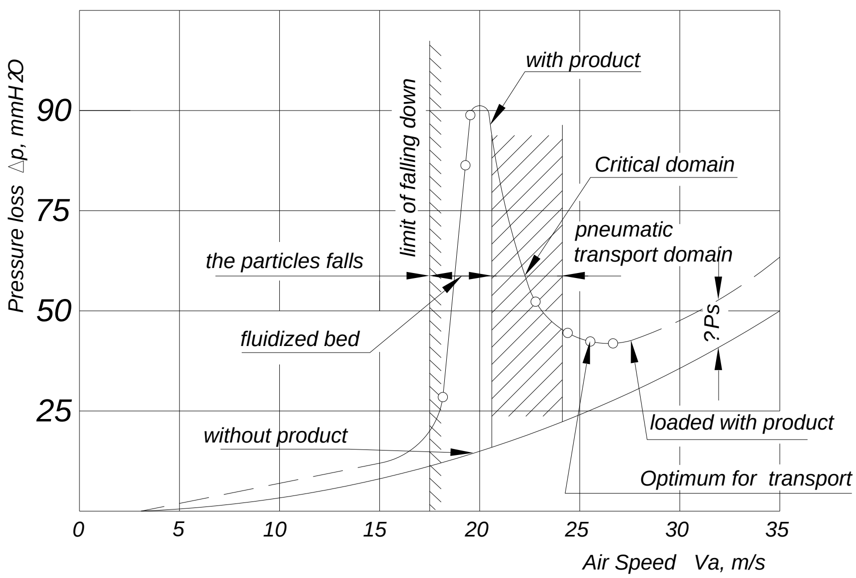

Fig. 3: Pressure loss variation in fluidized bed

It is obvious that the optimum point for pneumatic conveying is close to the critical domain, were the transport becomes unstable. Any further increase of the air speed is further influencing only the specific consumption of the pneumatic fan, by increasing it, since more air is transported for the same flow amount of product.

When discussing the energy efficiency of a pneumatic conveying system, let point out that the above graph is actually valid for each of the pipe from the system. Following this, it is clear that to have a system that operates at the maximum possible energetic efficiency, the system have to be tuned in such a way that each pipe to operate at the very vicinity of the optimum point.

A component part of almost any vacuum pneumatic conveying line in a flour mill is the bend. In almost any mills we can see large radius bends, as the common sense says that: the larger the radius-the lower pressure loss on the bend. According to some recent researches, this is actually not true. Despite the general practice, the tests shows that a larger radius bend, i.e. a bend with a 700 mm radius, has a higher pressure loss when compared with a 500 mm radius bend. But this doesn't mean that making the radius of a bend equal to zero will bring the pressure loss on the bend equal to zero. We will face the same problem mentioned above for the receiver of the equal to zero kinetic energy on the following moving direction. However, more tests should be carried out for to find the optimum point for minimum pressure loss in the bends. This could be connected also to the type of the product, and therefore personalizing the radius of bends for each type of the product within the intermediate stocks, would be an effective approach.

2.2.4. The cyclone.

The influence of the cyclone on the energy efficiency is manifested as a supplementary pressure loss. To minimize the pressure loss, the dimension of the cyclone should be increased, but this comes with the side effect of decreasing the separation efficiency. Decreasing the diameter of the cyclone and increasing the separation efficiency, actually decreasing the minimum diameter of the separated particles, causes a pressure loss increase on the cyclone by the square of the speed of the air. From practice, we can estimate the pressure loss on the cyclone as about 50-80 mmWC. For to keep the pressure loss at this level, or decreasing it, further tests have to be focused on increasing the separation efficiency of the cyclones, as it is later connected to the required surface of the filter. Lower cyclone separation efficiency require higher filtering surface and this is increasing the energy for to recover the product, generates products quality degradation by increasing the ash content, increasing the compressed air consumption for cleaning the filter, etc.

One very important part of the cyclone is the flap for to adjust the air flow amount. The idea is that, when considering one single pipe, by the fig. 2 we have to decrease the air flow in the pipe by adding artificial resistance to the pipe. This is a good solution for to give to the system the limit of air flow variation for each single pipe, as long as they are connected and a variation of air flow on one pipe, affects the air flow on all the other pipes.

For to have, at any given moment, a perfectly balanced system a continuous adjustment of these flaps should be made. Following these aim, we are developing dedicated device that will continue monitor and adjust the pressure loss in the line, and actually will continuous adjust the air flow amount on each pipe in such manner that all the time the air flow of the fan to be maintained at minimum necessary to the system.

2.2.5. The air-lock.

It has a double role: to separate the different pressure spaces and also to continuous unload the product separated from the cyclone, at a constant rate.

When discussing about the air-locks, two aspects should be considered: the first one is the construction tolerances and second one is the air flow brought to the system by the rotor. We have to point out that they are connected each other, since higher tolerances gives higher rate of false air. Using CNC production machines the tolerances are minimal and the false air inlet is lowered at minimum (fig. 4). The air flow brought to the system by the rotor itself, depends on some factors, such as the diameter, the length and the revolution speed. From the picture, for a certain operating regime of a 230 mm diameter air-lock at a vacuum of 1.000 mmWC for a revolution speed of 30 rev/min, we find a total parasite air flow generated by the air-lock of about 50 Nm^3/h. It may not looks a lot but this is only for one line and let consider for a 24 h of running: it gives a total amount of 1.200 Nm^3. Multiplied by the pressure and some corrections factors, we find that about 0,14 kwh are wasted only because of the air-lock. For a 250 to/24 h flour mill, that may have about 32 air locks, this gives about 4,5 kw, consumed each hour by the pneumatic fan only because of the air-locks. Almost one hour of the 24 h of operations, is consumed only for to compensate the air inlet due to the airlocks. Unfortunately, at this moment, there are not available on the market, better solution for this problem.

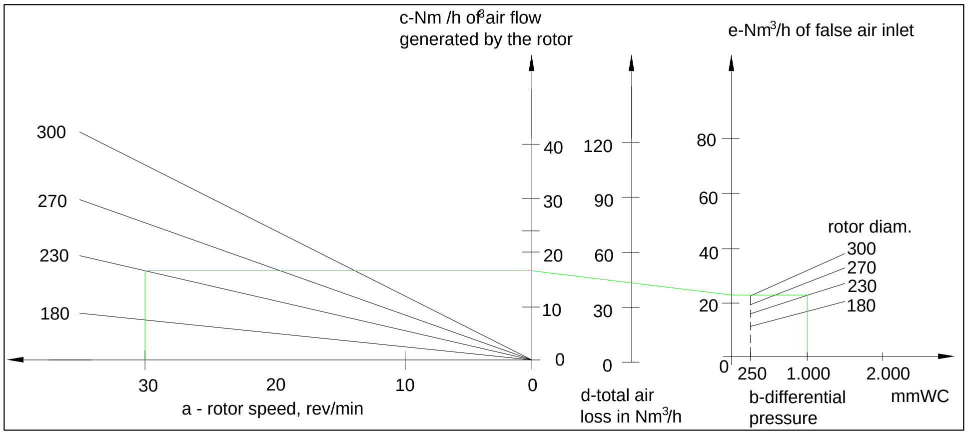

Fig. 4: Air flow loss on the air-lock

A new solution for to totally eliminate this shortcoming of air-locks is therefore more than necessary.

2.2.6. The filter.

By special filtering media, the product is separated from the air. A good filter will have a cleaning efficiency of more than 99,95 % of product separated from the incoming product flow. Leaving aside the filtering theory, this separation comes together with the cost of pressure loss generated by the filtering operation.

Fig. 5: Clogging regime proximity

For a nominal loading on the plant, usually the pressure loss on the filter is between 70 and 120 mmWC, more or less. A further increase of the pressure loss on the filter is immediately acknowledged by the miller because some pipes closes to an unstable operating regime (fig. 5) as the product inside the pipe start to agglomerate and makes “bundles”. Now, there is a clear connection between the pressure loss on the filter and the maximum capacity of the plant. Returning to the fig. 2, considering the pressure variation Dx as for one single line connected to the filter, actually from this total Dx any increase of the pressure loss on the filter (or any other component) will decrease the remaining available energy for to transport the product. In our opinion, to have a maximum energy efficiency of plant, the pressure on the filter have to be controlled and, further, maintained at a certain value, let say 100 mmWC. In this situation, for a good designed plant, the energy consumption will be minimum, as the energy of the fan is mainly determined by the pressure and the air flow amount. The conversion of the dynamic pressure into static pressure is not 1:1, is even less than 1, and this explain why do we have a reduction of the consumed power by the fan when the plant is at nominal load condition. This solution bring also one more advantage since the compressed air consumption will be reduced at minimum amount.

2.2.7. The product to be transported.

One more and perhaps the most important factor for the vacuum pneumatic conveying of the intermediate stocks in flour milling is the product to be transported (fig 6).

Fig. 6: Some samples of the intermediate stocks used in tests

The most important factor of all that at the end define the specific energy consumption of pneumatic conveying is the mixing ratio between the product and the air. From specialty literature, one can find good recommendations for this parameter. But the tough question is: what is the limit of vacuum pneumatic conveying? How can we define it and what does it mean? From our intensive researches we found out that this limit is connected to a specific constant of the product, namely Clogging Constant, expressed as: [kg of product/kg of air/m^2 of cross section area of the pipe]. Using this constant and considering the initial conditions for the air speed and the pipe diameter, the clogging condition for each single pipe is determined.

3. Our solution.

3.1. Presentation.

As a result of all the above statements, it is obvious that to handle all the mentioned critical points would require from the miller a lot of time. More, this is something that have to be done continuously through the plant, day and night, summer or winter. Only a global approach of the problem will give the best results. While at the moment on the market there are available partial solutions, like for example using electronic revolution speed control for the fan, or automatic flaps for the cyclones, or differential pressure controlled filters, only a total control will give the best results. Considering the fan, the modern solution is to use electronic revolution speed controlling device. These device especially are extremely efficient, since a reduction of the revolution speed by let say 5 %, will have an effect of reduction of the air flow amount of 5 %, a pressure reduction of about 10,25 % and total power saved of about 15,76 %.

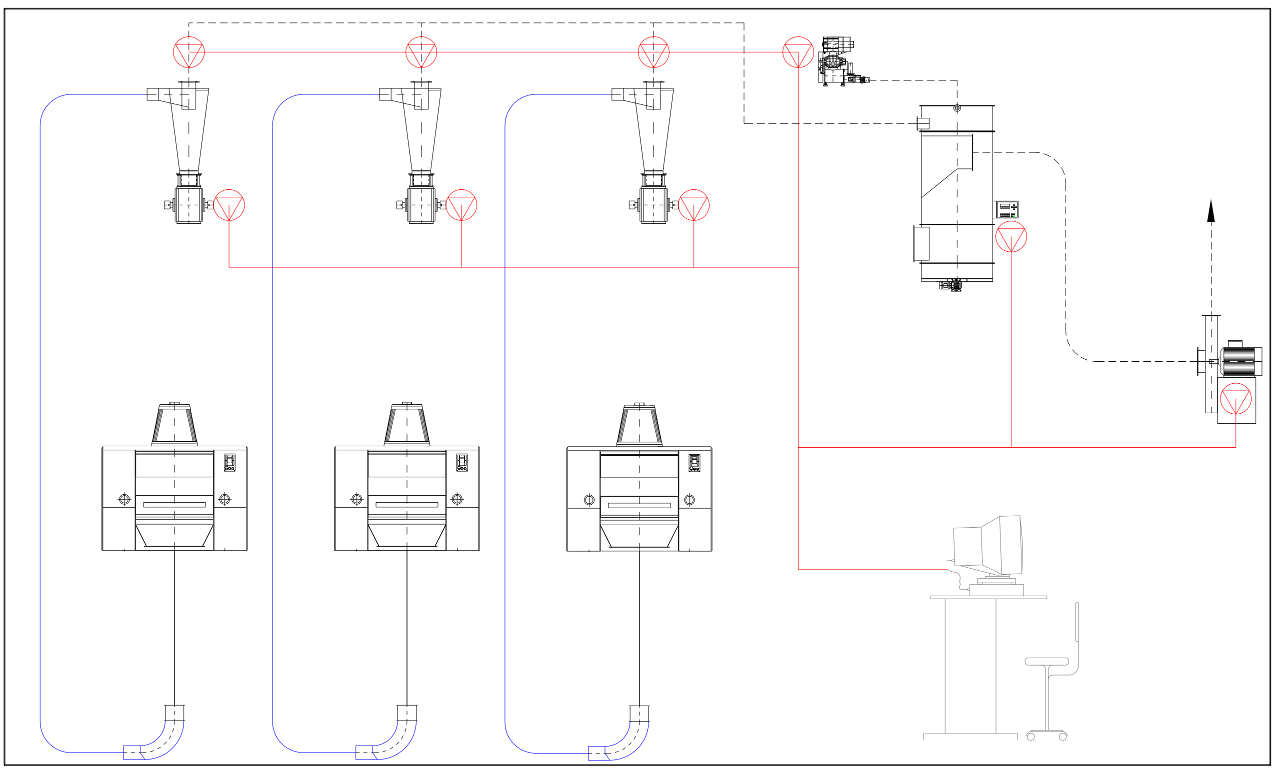

Fig. 7: General Configuration of the ***Pneu-Matic®*** control principle

The main problems that remains is that to have the system designed as to work at the limit of conveying regime, means at the minimum air flow and pressure.

The solution we are proposing involves two steps:

- The first part implies a proper designing of the system as pipe diameters, cyclones, air-locks, filter, blower compressor for filter and also the fan
- The second step includes some hardware equipment and a dedicated unit with specialized software, which we are calling ***Pneu-MATIC®*** (fig. 7) and that is under developing together with our partner Alapala. The solution, that we hope to be available on the market soon, is a total one and solves most of the above mentioned critical points, except for the air-locks, where out of that to control the revolution speed and to maintain at the minimum the parasite air flow inlet, there is no other solution available on the market at this moment, for this kind of application. The ***Pneu-MATIC®*** will totally control your plant doesn’t matter there is winter or summer, or one line is higher loaded and some other under loaded, will adjust the consumption also of the blower compressors supplying air for to clean the filter, and so on.

From our researches it is also obvious that the air leaving the system still has an amount of energy. Something similar to the Law of Betz’s, tells us that we cannot extract all the energy from the air, at least the energy corresponding to the floating speed of the product, in the given conditions of particle mean diameter, the load of the pipe and pipe diameter.

One interesting fact we found important in terms of energy consumption, is that the floating speed is connected to the ratio between the mean particle diameter and pipe diameter. For a specific product, for the same specific load with product and a given available pressure of the fan, the floating speed decreases with the pipe diameter decrease, i.e. the air flow velocity required for to make the transport of the same product, is lowering as the pipe diameter decreases. Therefore, were reasonable to use, we would recommend that instead of a larger diameter pipe, let say 150 mm, to use 2 lines of the same total cross section area. The air velocity required for to make the transport is lower, and therefore the air amount is lowered as well as the pressure, and at the end the installed power of the fan is decreasing somehow by the third power of the product between the air flow and pressure.

3.2. Estimating the effects of the system implementation.

Following the present proposal, one can ask: after implementing all this system, and making the investment, what would it bring back to me? What will be my advantage?

Let’s try to quantify:

- Considering again one flour milling unit, cap. 250 to/24 h
- In general, the installed power on the pneumatic system for this unit, is about 130 kw
- We do not make any mistake by estimating a consumption reduction of a 20 %
- A normal operating time for such a flour mill could be a 25 days per month, for 12 months
- Total energy saving will be: 187.000 kw/year
- An average price for kwh is let say: 0,10 Euro
- This will mean in terms of saving, about: 18.700 Euro/year/unit
- For a 20 years of operation, the normal life time of a flour mill, it means 374.000 Euro
- And for a company, that operates 5 units, will bring a total of more than 1.870.000 Euro.

Thank you very much for your attention.

Prepared by,

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