DESIGN PROCEDURE FOR CYCLONES USED IN LOCAL EXHAUST VENTILATION SYSTEMS

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ABSTRACT

The local exhaust ventilation systems used to capture the air contaminated with dusts are provided with different kinds of equipments to recover the captured dusts. Among them, the cyclone is the most common equipment when the dust toxicity is not very high.

The overall collection efficiency in cyclones has been studied experimentally as a function of the inlet air velocity to the equipment. The goal was to maximize the overall collection efficiency, minimizing at the same time, the system energy consumption. Besides this, the exhaust system duct diameter is related with the cyclone diameter. This is important for the correct system design. Experimental work has been done in a Pilot Plant ventilation system, measuring dust transport velocities, collection efficiencies and pressure drops in the cyclone. The main conclusion is that the cyclone design using high inlet velocities is not convenient from the processsing and economical points of view, because the overall collection efficiency is decreased and the exhaust system pressure drop (and therefore the required power) is increased.

INTRODUCTION

The local exhaust ventilation systems used to capture dusts are important in many kinds of industrial plants, such as those of mining industry and extractive metallurgy processes. In these industrial processes dust is produced in many operations related with the handling and processing of dry solid materials like grinding, transport and storage of powders, roasting of minerals, etc.

Proper design of local exhaust ventilation systems is important due to different factors:

a- To avoid the air contamination in the industrial work environment. To get this goal the dust must be captured at its production sources by exhaust hoods.

b- To avoid the external atmospheric pollution which can produce contaminative effects in soils, superficial water and ground water, with nocive effects in persons, animals and vegetables.

c- To increase the powder material recovery in the industrial plant.

As it was said, the high efficiency cyclone is the most used equipment. Cyclone separators utilize a centrifugal force generated by a spinning gas stream to separate the particle matter from the carrier gas. When the particle matter to be

separated is a high toxic dust it is necessary to use

equipments that achieve higher efficiencies for removing small particles, like fabric filters or electrostatic precipitators.

The cyclones great advantages are their simplicity and low investment cost, but if their design is not correct, they can produce high pressure drops in the systems, increasing its operating cost. Many designs of high efficiency cyclones have been done with small differences in them (Stairmand, 1951; Lapple, 1951; Zenz and Othmer, 1960). This job has been done using a cyclone with the Lapple's design which is the most common kind of cyclones used in exhaust systems. Figure 1 shows the design configuration of the used cyclone, in which $D_c = 20$ cm, and where all dimensions are related to the cyclone diameter, D_c.

The most satisfactory expression for cyclone performance is still the empirical one developed by Lapple (Lapple, 1951) and confirmed by a theoretical model (Zenz and Othmer, 1960). It correlated the collection efficiency in terms of the cut size, d_c. This is the size of those particles that are collected with 50 % efficiency. Particles larger than d_c will have a collection efficiency greater than 50 % while the smaller particles will be collected with lesser efficiency. The cut size is given by:

$$d_c = 0.85\sqrt{\frac{\mu D_c}{N_c\, v_c\, (\rho_s - \rho)}} \qquad (1)$$

where:

d_c: cut diameter, cm

D_c: cyclone diameter, m

μ: gas viscosity, g/cm s

ρ: gas density, g/cm^3

ρ_s: solid particle density, g/cm^3

v_c: cyclone inlet velocity, m/s

N_c: number of turns a gas makes in traversing the cyclone. Lapple takes $N_c = 5$ (Perry, 1963)

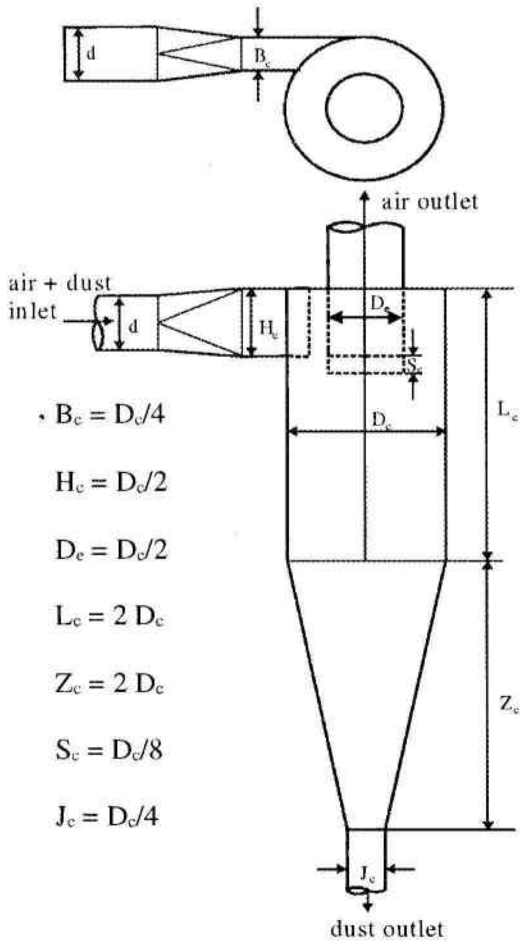

Figure 1: Design configuration of Lapple's cyclones

The cyclone inlet is rectangular, and the gas inlet velocity to the cyclone is defined as:

$$v_c = \frac{Q}{A_c} = \frac{Q}{B_c\, H_c} \qquad (2)$$

where:

Q: air flow in the exhaust system, m^3/s

$A_c = B_c H_c$: cyclone inlet cross-sectional area, m^2

The most common way of expressing the cyclone efficiency is in terms of the weight of material caught or retained by the cyclone compared to the total amount entering the cyclone. This is known as overall efficiency or total efficiency, η, and it is usually expressed as a percentage (Rao, 1991).

$$\eta = 100 \times \frac{\text{Weight of material collected}}{\text{Total amount of material entering}} \qquad (3)$$

In particulate collection systems, the efficiency of collection varies with particle size. This variation is often expressed in the form of fractional efficiencies for particles of different size-range (Rao, 1991). In many cases a good approximation is obtained if the overall collection efficiency is taken as equal to the cumulative percentage of material with size particle $d_p > d_c$ in the dust fed to the cyclone (Perry, 1963).

The cyclone used in an exhaust ventilation system must be designed to get a high overall collection efficiency keeping the pressure drop into an admissible range.

Equation (1) shows that, for given values of the other variables, it is:

$$d_c = \frac{k}{\sqrt{v_c}} \qquad (4)$$

where the constant k depends on the values of D_c, μ, ρ_σ and ρ for a given case.

Then, according to Perry's approximation (Perry, 1963) it should be (approximately):

$$\eta = k'\sqrt{v_c} \qquad (5)$$

where k' is another constant.

It has been determinated experimentally that for a cyclone with $D_c = 0.20$ m, working with magnetite dust ($\rho_s = 4.7$ g/cm^3) and air ($\rho = 1.20 \times 10^{-3}$ g/cm^3 and $\mu = 0.00018$ g/cm s), k' = 21.5. Then, for this particular case, it is:

$$\eta = 21.5\sqrt{v_c} \qquad (6)$$

This relationship is represented in Figure 2.

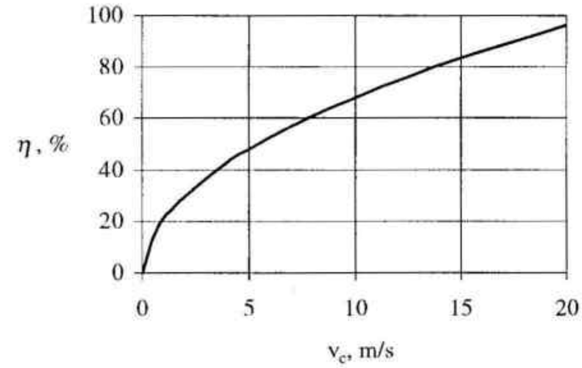

Figure 2: Graphic representation of η vs. v_c

EXPERIMENTAL RESULTS

Minimum transport velocity, v_{min}, in the exhaust ventilation duct was taken as the saltation velocity (Pocoví et al., 1997). This is the average pipe line velocity below which the particles begin to bounce (that is moving along in series of short intermitent jumps). An exhaust ventilation system with a duct diameter of 70 mm and total length of

approximately 5 m was used. It was constructed of PVC, but with a section of 1 m made oftransparent plastic, to permit the observation of the behaviour of the flowing mixture of air and dust. A cyclone collector (as the one represented in Figure 1) was used to remove the dust from the air and an exhaust centrifugal fan was used to produce the required air flow through the system. The cyclone pressure drop was measured with an U-tube manometer connected to the cyclone inlet air duct and to the oulet air duct. The volumetric air flow rate measurement was made by the Throat Suction Method (ACGIH, 1986; Pocoví, 1999). This method involves the measurement of the static pressure by means of a U-tube manometer which is situated three duct diameters downstream from the duct inlet. The air flow was controlled using a butterfly valve.

For each mineral dust studied v_{min} was determined and then, working with different flows, the values of cyclone pressure drop (ΔP) and overall efficiency (η) were also measured. ΔP was proportional to v_c^2, as it is expressed in all published correlations (Perry, 1963; Rao, 1991). The values of η were expressed as a function of the inlet air flow velocity to the cyclone given as a dimensionless relation v_c/v_{min}:

$$\eta = f\left(\frac{v_c}{v_{min}}\right) = f(\phi) \qquad (7)$$

where $\phi = v_c/v_{min}$ is the dimensionless air inlet velocity. The mineral dusts studied are included in Table I.

Table I: Mineral dusts studied experimentally. Particle size $d_p < 147$ μm

Mineral dusts	ρ_s (g/cm^3)	v_{min} (m/s)	$\phi_{opt.}$
Ulexite	2.11	4.0	1.40
Colemanite	2.42	4.5	1.45
Sand	2.91	4.8	1.60
Clinker	3.10	4.9	1.70
Magnetite	4.82	5.8	1.80
Galena	6.70	6.4	1.85

As examples of the experimental results obtained, Figures 3 and 4 show the representation of the relationship (7) for colemanite and magnetite.

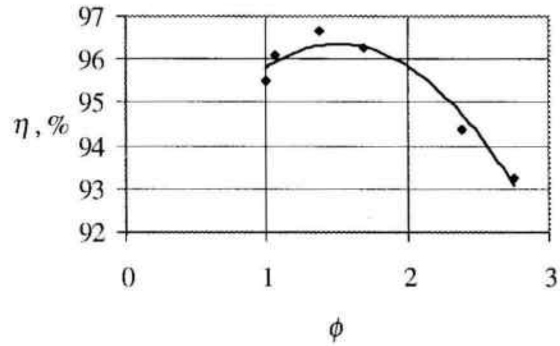

Figure 3: $\eta = f(\phi)$ for colemanite

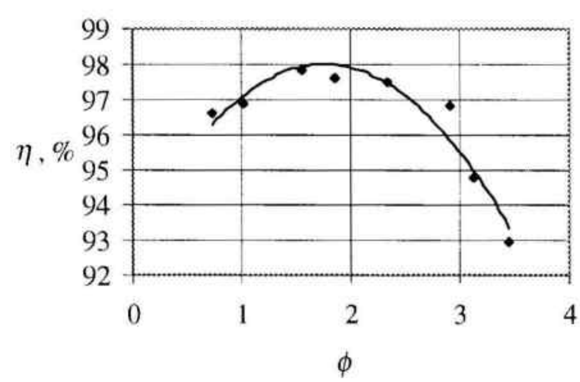

Figure 4: $\eta = f(\phi)$ for magnetite

Experimental results indicate that the Equation (6) and its graphic representation given in Figure 2, or similar equations that can be derived for other minerals, are only valid within low velocities ranges of the air inlet velocity to the cyclone. Equation (6) gives a parabolic relationship between η and v_c, indicating that there is a proporcional increase of η with $v_c^{1/2}$. But experimental curves, as the ones corresponding to Figures 3 and 4, show than η reaches a maximun value (η_{max}) for a given optimum value of ϕ ($\phi_{opt.}$). That is to say:

$$\text{For } \phi = \phi_{opt.} \quad \text{is } \eta = \eta_{max} \qquad (8)$$

According to Table I the values of $\phi_{opt.}$, that give the maximum value of η, are in the range of 1.4 to 2. This means values of inlet velocity, v_c, between (1.4 to 2)v_{min}. These results are mentioned without enough precision in another paper (Casal and Martínez-Benet, 1989).

This fact has a great importance because many authors studying cyclones design recommend to carry out it using an inlet air velocity of v_c = 15 m/s or higher than it (up to 21 m/s) (Perry, 1963; Rao, 1991). These values are much higher than the given by the experimental values of Table I and produce a decrease in η and a corresponding increase in ΔP (this produces an increase in the energy consumption of the exhaust ventilation system).

The $\phi_{opt.}$ values can be correlated with the dusts densities (ρ_s). This is shown in Figure 5.

The empirical equation that corresponds to this experimental curves is:

$$\phi = 1.21\ \rho_s^{0.24} \qquad (9)$$

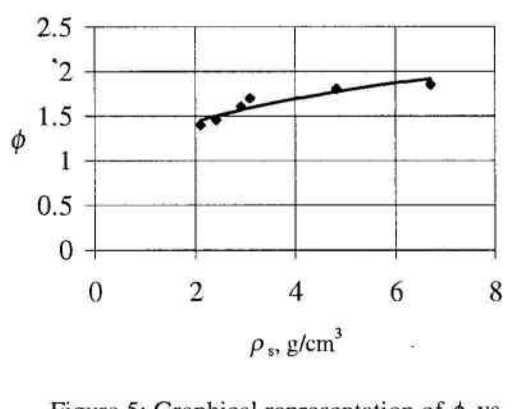

Figure 5: Graphical representation of ϕ vs. ρ_s

CONCLUSIONS

To carry on the cyclone design for an exhaust ventilation system, the first requirement is to know the diameter, d, of the exhaust duct, which is a function of the air flow (Q) required to solve the ventilation problem. Then:

$$\frac{Q}{v_d} = \frac{\pi\, d^2}{4} \quad \rightarrow \quad d \qquad (10)$$

where:

v_d: design velocity of the exhaust duct, m/s

The design velocity, which is the velocity used to operate the system, has to be higher than v_{min}, having value enough to protect the system against different practical contingencies, such a sticky or wet material, electrostatic effects, etc. The relation between the two velocities can be written as:

$$v_d = F_s\, v_{min} \qquad F_s > 1 \qquad (11)$$

where F_s is a safety factor higher than one. Taking values of F_s = 3 - 3.5, the v_d values obtained are in the order of the practical values recommended by the Industrial Ventilation Manual (ACGIH, 1986).

If it is not possible to determine v_{min}, the following empirical relationship can be used. It agrees quite well with the experimental values (Pocoví, 1997):

$$v_{min} = 5.4\, \rho_s^{0.37} d_p^{0.26} \qquad (12)$$

where v_{min} is given in m/s, ρ_s expressed in g/cm^3 and d_p in mm.

According to the equation of continuity applied to incompressible fluids (in ventilation, air can be considered as an incompressible fluid) it is:

$$Q = v_d \frac{\pi\, d^2}{4} = v_c B_c H_c \qquad (13)$$

If $v_d = F_s\, v_{min}$, $v_c = \phi_{opt.}\, v_{min}$ and considering a Lapple's design cyclone, it is:

$$F_s \frac{\pi\, d^2}{4} = \phi_{opt.} \frac{D_c}{4} \frac{D_c}{2} \qquad (14)$$

and then:

$$D_c = d \sqrt{\frac{2\pi\, F_s}{\phi_{opt.}}} \qquad (15)$$

This equation is very important because it expresses the cyclone diameter in terms of the duct diameter.

With this design criterium the cyclone is operating near the condition of maximum overall efficiency and the pressure drops are sharply lower than the corresponding values obtained using the traditional method.

REFERENCES

American Conference of Governmental Industrial Hygienists. Industrial Ventilation. A Manual of Recommended Practice. 19th Edition, 1986.

Casal, J., Martínez-Benet J.M. Cálculo y diseño de ciclones. Rev. Ingeniería Química, Madrid, p.115, Febrero 1989.

Lapple, C.E. Processes use many collection types. Chem. Eng.,USA, v.58, p.145, 1951.

Perry, J.H. Chemical Engineering Handbook. Fourth Ed. Mc Graw Hill Book Company, USA, 1963.

Pocoví, R.E., Villaflor G., Flores J.E. Minimum transport velocities of mineral and metallic dusts in exhaust systems. Proceedings of the 5th International Symposium on Ventilation for Contaminant Control. Ottawa, Canada, 1997.

Pocoví, R. Ventilación Industrial. Ed. Magna Publicaciones. Universidad Nacional de Salta, Argentina, 1999.

Rao, C.S. Environmental Pollution Control Engineering. John Willey & Sons, USA, 1991.

Stairmand, C.J. The design and performance of cyclone separators. Trans. Inst. Chem. Eng., v.29, p.356, 1951.

Zenz, F.A. and Othmer, D.F. Fluidization and fluid particle systems. Reinhold, New York, 1960.