Brazilian Journal
of Chemical
Engineering

ISSN 0104-6632
Printed in Brazil

Vol. 20, No. 04, pp. 435 - 443, October - December 2003

ANALYSIS OF THE EFFICIENCY OF A CLOTH CYCLONE: THE EFFECT OF THE PERMEABILITY OF THE FILTERING MEDIUM

M.V.Rodrigues, F.O.Arouca, M.A.S.Barrozo and J.J.R.Damasceno*

Universidade Federal de Uberlândia, Faculdade de Engenharia Química, Bloco K,
Campus Santa Mônica, Phone (55-34) 239-4189, Fax (55-34) 239-4188
CEP: 38400-902, Uberlândia-MG, Brazil
E-mail:jjrdamasceno@ufu.br

(Received: July 6, 2002 ; Accepted: May 19, 2003)

Abstract - The cloth cyclone is a solid-gas separation device that consists of a Lapple cyclone whose conical section has been replaced by a conical filtering wall. The present research was undertaken with the aim of examining the influence of a conical filtering section made of three different materials on the performance of a Lapple design cyclone. The overall efficiency and pressure drops of the cloth cyclone and a conventional one were compared. The effect of the filtering medium on the behavior of the cyclone was also evaluated using an equation that correlates the cut size diameter with the operational conditions, the properties of the gas-solid system and the resistance of the filtering medium. The experimental results demonstrated that the overall efficiency of the conventional cyclone was similar to that of the proposed device, with the latter displaying a reduction in pressure drop. Consequently, energy costs are lowered when cloth cyclones are used.

Keywords: cloth cyclone, gas-solid separation, filtering cyclone.

INTRODUCTION

Cyclones are used in the chemical industry to separate particles in a gaseous current. They are composed of a cylindrical part coupled to a conical section. The separation inside occurs because of the action of the centrifugal force field as a result of the shape of the equipment and of the manner in which the suspension is fed in. Its simplicity of construction, low energy requirements, and ability to operate at high temperatures make the cyclone an attractive option for cleaning up gases (Koch and Licht, 1980).

The first studies with filtering equipment of the cyclonic type were conducted by Barrozo et al. (1992) with filtering hydrocyclones. Aiming at the association of two separation processes, researchers in the Chemical Engineering Department at the Federal University of Uberlândia proposed a modification of the conventional hydrocyclone. The conical section of a Bradley hydrocyclone was replaced by a conical filtering wall. The equipment created was then denominated the filtering hydrocyclone. The advantages of this association are somewhat evident. If this device is viewed as a hydrocyclone, it offers the advantage of increasing the volumetric capacity of the conventional equipment, owing to a new outgoing stream, the filtrate stream. As a filter, this device offers the advantage of continuous operation because the high velocity of the suspension circulating within the equipment does not allow the formation of filter cake.

Souza (2000) quantified the performance of this equipment as a function of the resistance of the filtering medium used. This author also observed that the simple incorporation of a conical filtering wall in a Bradley hydrocyclone produced a significant

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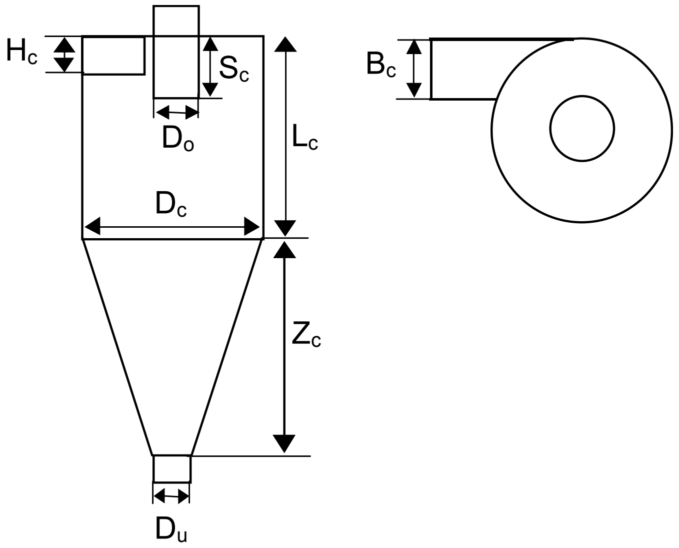
*To whom correspondence should be addressed increase in the values of the volumetric flow rates of the feed, thus providing smaller energy costs.

Based on the results of previous research, the cloth cyclone was developed. This cyclone is of the shape proposed by Lapple (Dc=0.194 m) as shown in Figure 1; however, its conical part is made of cloth.

The substitution of a filtering medium for the metallic conical part can cause a reduction in the pressure drop of the cyclone (ΔP), allowing the air to pass through the cloth as shown in Figure 2 (Rodrigues, 2001). As a result, the equipment can operate with a considerable savings of energy.

The objective of the present paper was to compare the values of overall efficiency of separation, cut size diameter and Euler numbers for cloth cyclones constructed with different filtering media with those for a conventional cyclone of the same shape. The influence of filtering medium on the behavior of the cyclone was also studied. An equation that relates cut size diameter to the operational conditions, properties of the solid-gas system and resistance of the filtering medium was proposed.



Where:

$B_c/D_c=0.25$;
$H_c/D_c=0.50$;
$D_o/D_c=0.50$;
$D_u/D_c=0.25$;
$S_c/D_c=0.62$;
$L_c/D_c=2$;
$Z_c/D_c=2$;

Figure 1: Schematic representation of the Lapple cyclone family. (D_c=0.194m).

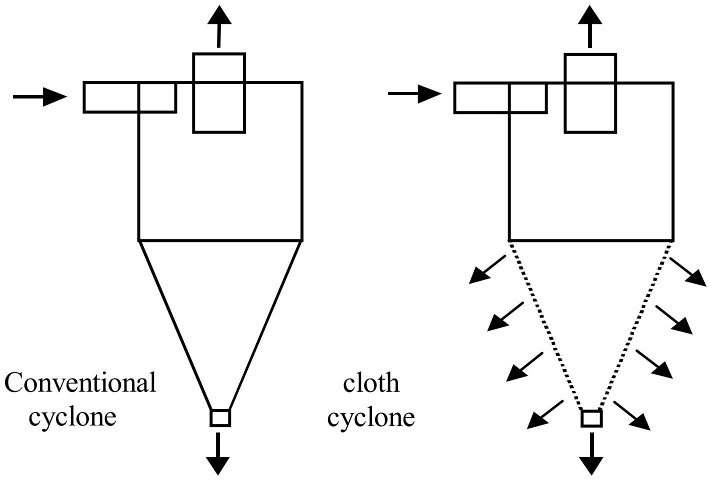


Figure 2: Comparison between Lapple conventional and filtering cyclones.

EQUATIONS

Massarani (1997) has presented the only systematic design for all the families of cyclones and hydrocyclones based on the residence time theory (Svarovsky, 1984). In this theory, a particle of a given size will be collected if the time it remains inside the cyclone is equal to or longer than the time necessary for it to reach the wall. Cut size corresponds to the size of the particle which, if entering precisely at the centre of the inlet pipe, will reach the wall in residence time (t). Massarani`s equation related cut size diameter (d_{50}); parameter (K) which depends on the shape of the cyclone; physical properties of the system (μ, ρ e ρ_s); and volumetric flow rate of the feed (Q), as shown in equation (1).

$$\frac{d_{50}}{D_c} = K\left[\frac{\mu D_c}{Q(\rho_s - \rho)}\right]^{0.5} .g(c_v) \tag{1}$$

where function g (c_v) corrects for the effect of concentration on cut size diameter. For experiments with a highly diluted suspension $g(c_v)$ is approximately equal to one (Massarani, 1997).

The other important parameter in the cyclone study is the Euler number (Eu). This dimensionless number relates the pressure drop in the cyclone (ΔP) with the kinetic energy per unit volume of feeding. The larger the values of the Euler number, the larger the energy costs required by the equipment. The Euler number is defined by equation (2).

$$Eu = \frac{2.(-\Delta P)}{\rho.u_c^2} \tag{2}$$

where u_c is the average velocity of the fluid in the cylindrical section of the cyclone.

Parameter K and the Euler number (Eu) for the Lapple cyclone, as well as the range of gas velocity in the feed section (u), according to Massarani (1997), are shown in Table 1.

The overall efficiency of separation ($\bar{\eta}$) was determined by the ratio between the mass of particles collected in the underflow and the mass of particles fed into the cyclone. The individual efficiency of separation (η) is a parameter related to the efficiency of separation of the equipment for only one particle size. This variable is calculated based on knowledge of the overall efficiency of separation ($\bar{\eta}$) and the grade distributions of the particles in the underflow and feeding, as in equation (3). For an individual efficiency of separation of 50%, the cut size diameter is given by

$$\eta = \bar{\eta}\frac{dX_u}{dX} \tag{3}$$

Determination of the Resistance of the Filtering Medium

Since the conical sections of cloth cyclones are permeable, the gas flows through the filtering medium. By applying the equation of motion in cylindrical coordinates and Darcy's Law to the conical wall, it is possible to obtain a simplified mathematical model for this filtration (Rodrigues, 2001).

For a compressible radial flow obeying Darcy's Law across the filtering cone in steady state, as shown in Figure 3, the equation of motion in cylindrical coordinates yields

$$-\frac{dP}{dr} = \frac{\mu}{K_m}q = \frac{\mu}{K_m}\frac{G_m}{\rho A_{lateral}} \tag{4}$$

where dP/dr is the pressure gradient across the porous wall, G_m is the fluid mass per unit of time, K_m is medium permeability, ε is medium thickness and $A_{lateral}$ is the lateral area of the cone surface. K_m, $A_{lateral}$ and ρ (ideal gas) might be expressed as follows:

$$R_m = \frac{\varepsilon}{K_m} \tag{5}$$

$$A_{lateral} = 2\pi r(L - L_C) + \frac{\pi}{2}(L - L_C)(D_C - D_{inf}) \tag{6}$$

$$\rho = \frac{PM}{RT} \tag{7}$$

where L is cyclone length, L_C is length of the cylindrical section, D_{inf} is internal lower diameter of the cone, P is absolute pressure of the gas, M is molecular weight of the gas, R is universal constant of gases and T is absolute temperature.

Substituting Equations (5), (6) and (7) into Equation (4) gives

$$-dP = \frac{\mu R_m}{\varepsilon}\frac{RT}{PM} G_m \frac{dr}{2\pi r(L - L_C) + \frac{\pi}{2}(L - L_C)(D_C - D_{inf})} \tag{8}$$

For a homogeneous distribution (i.e., R_m does not depend on the position inside the cone) and an isothermal system, Equation (8) can be integrated between $(D_{inf}/2)$ and $(D_{inf}/2+\varepsilon)$. By doing this and isolating G_m, we obtain Equation (9):

$$G_m = \left[\frac{\mu R_m RT}{\pi(L-L_1)\varepsilon M}\ln\left(\frac{D_{inf}+D_C}{D_{inf}+D_C+4\varepsilon}\right)\right]^{-1} P^2 + \left[\frac{\mu R_m RT}{\pi(L-L_1)\varepsilon M}\ln\left(\frac{D_{inf}+D_C}{D_{inf}+D_C+4\varepsilon}\right)\right]^{-1} P_{atm}^2 \qquad (9)$$

Thus, Equation (9) can be written as a function of just two parameters that contain whole properties of the system:

$$G_m = aP^2 + b \qquad (10)$$

Using experimental data for G_m and P it is possible to evaluate parameters *a* and *b*. Once the values of those parameters are known, the resistance of the filtering medium can be calculated easily according to Equation (9).

It could be argued that resistance of the filter cake should be included in the formulation as in flat filtration. Nevertheless, during the experiments it was verified that no cake is formed, owing to the high tangential velocity of the suspensions within the cyclones.

EXPERIMENTAL METHODOLOGY

Materials

The solid used in the experiments was phosphate powder from Patos de Minas (Minas Gerais, Brazil) with a density of (3090±30) Kg/m^3, as determined by hot picnometry. The granulometric distribution of this material was obtained through LASER diffractometry with a Malvern Mastersizer Microplus (MAF 5001). The model that showed the best adjustment to the granulometric distribution was the Rosin-Rammler-Bennet (RRB) (Allen, 1997). Figure 4 shows the curve representing the granulometric distribution of the phosphate powder, as well as the adjustment of the parameters of the RRB model.

Experimental Apparatus

Figure 5 shows a schematic representation of the experimental apparatus.

The air was pumped into the system by a 5 HP blower (6). The flow rate was regulated by a valve (5) installed in a bypass tube. The solids were fed through a rotative plate (4) located inside an acrylic box. Silica gel was placed inside the box, with the purpose of controlling the humidity of the solid-gas system. The flow rate of the air was measured by a orifice plate (3) connected to a "U" tube manometer (2). The pressure drop between the feeding and the overflow in the cyclone was measured with a "U" tube manometer (2).

Cyclones Studied

The conventional cyclone, with the conical part made of metal (cyclone M), and the filtering cyclones, with the conical part made of polypropylene cloth (cyclone PP), polyacrylate (cyclone PA) and polyester (cyclone PE), were analysed. In each case, the gas velocity in the feeding section was varied according to Massarani's proposal (1997).

Determination of Resistance of the Filtering Medium

The resistance of the cloth was obtained with Equation (8). In order to apply this equation to determine the filtering resistances, experiments were carried out in a simple unit, similar to the one shown in Figure 5. The underflow orifice and overflow tube were closed, and the only way the air could exit was through the cloth (conical part). The flow rates and pressure drops were varied and measured for each cone.

Table 1: Parameters of the Lapple cyclone configuration.

Operational Conditions [m/s]	K [ ]	Eu [ ]
$6 < u < 21$	0.095	315

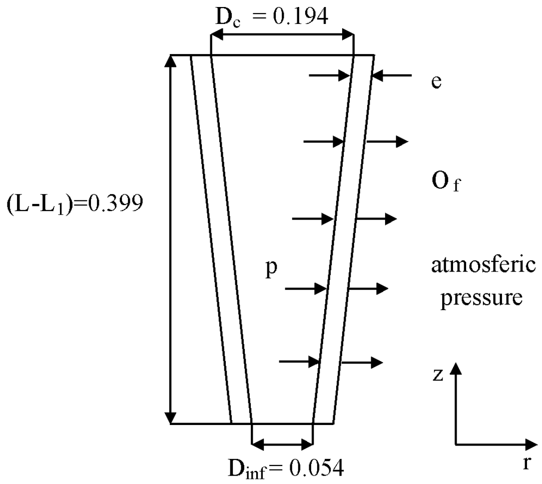


Figure 3: Radial flow of the filtrate across the filtering cone (dimensions in meters).

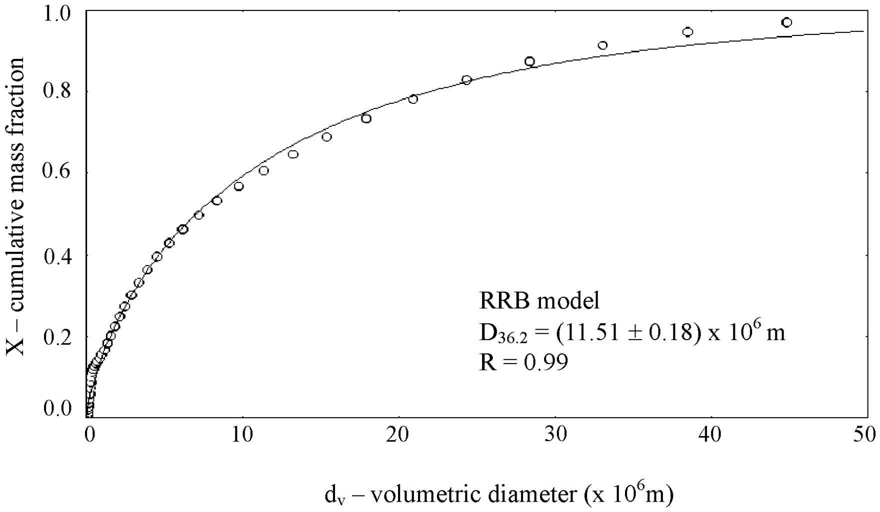


Figure 4: Particle size distribution of the phosphate oxide (P_2O_5).

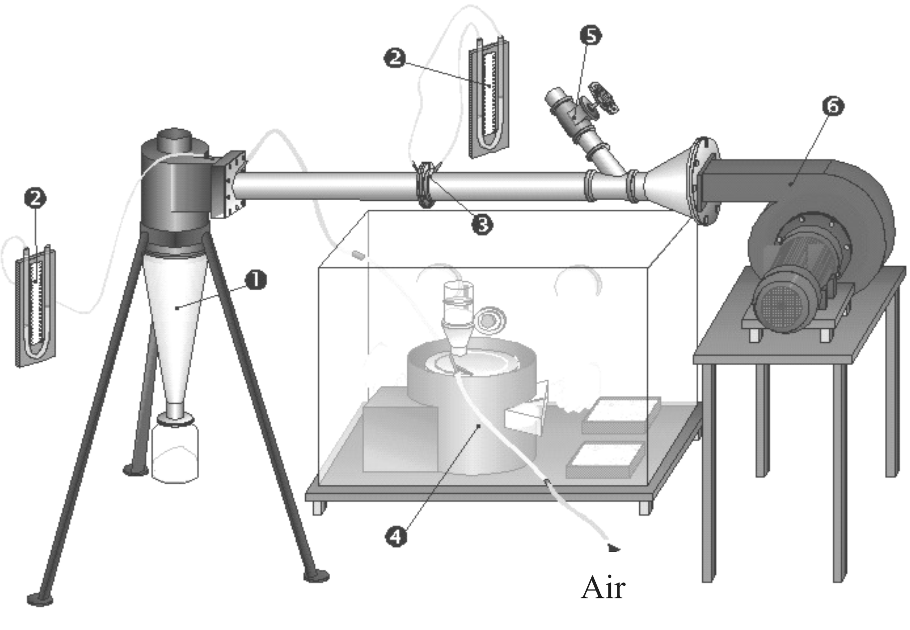


Figure 5: Experimental apparatus.

RESULTS AND DISCUSSION

During the experiments an initial deposit of the powder could be observed and its adhesion to the surface of the filtering medium. However there was no increase in thickness of the filtration cake. This was verified by maintenance of a constant pressure drop in the cloth cyclone for long periods during the experiments. This indicated that the stress tension produced by the centrifugal movement of the gas should have impeded cake formation.

Table 2 contains the results for flow rate (Q), overall efficiency ($\bar{\eta}$), pressure drop (ΔP), Euler number (Eu), cut size diameter (d_{50}) and resistance of the filtering medium (R_m), obtained for the each cyclone. It can be observed that, for the same feed flow rate, the cloth cyclones had values of overall efficiency and pressure drop lower than those of the conventional cyclone (M). The PA cyclone had the lowest values. The cut sizes obtained for the cloth cyclones were bigger than those obtained for the conventional one, indicating the lower separation efficiency of the fine particles.

The first consequence of incorporation of the filtering medium in the cyclone was a fall in the Euler number. It can also be observed in the Table 2 that the Euler number decreases when the resistance of the filtering medium decreases.

These results are consistent, because when the permeability of the filtering medium increases, the importance of the alternative flow through the cone surface increases. The Euler numbers shown in Table 2 express this effect, indicating that cloth cyclones have ratios of pressure drop to feed flow rate that are smaller than those for conventional cyclones.

Therefore, the cloth cyclones can operate with higher feed flow rates for the same pressure drop. In addition, for the same feed flow rate, the cloth cyclone can be operated with smaller pressure drops and, consequently, with a lower consumption of energy, as shown in Figure 6.

Starting from the experimental data obtained it was possible to estimate parameter K and the Euler number for each cyclone. The values of these parameters and theirs respective deviations are shown in Table 3.

The value of the Euler number found for the metallic cyclone was very close to 315, the value considered by Massarani (1997) for cyclones of the Lapple family. However, Massarani`s value for parameter K (K=0.095) was not observed in the present work (K=0.066). This difference can be attributed to the flange at the junction of the cylindrical and conical parts of the cyclone, so that the filtering cloth could be substituted for the metallic conical part. Moreover, the Malvern counter distributes sizes based on the diameter of the sphere with a volume equal to that of the particle (dp), while the diameter of the centrifugal equipment is the Stokes diameter (dst). According to Allen (1997) to relate the volumetric diameter to the Stokes diameter determination of sphericity is necessary.

For the conventional cyclone, parameter K only depends on the shape of the equipment (Massarani, 1997). However, the experimental results show different values for each filtering cyclone studied. Equation (1) indicates that the larger the values of K, the larger the values of cut size and the smaller the efficiency values. The difference between the K values can be attributed to the difference in permeability of the filtering media. Therefore, K can be expressed as a function of resistance of the filtering medium, K' = K.f(R_mD_c).

Based on the previous discussion, it is necessary to obtain a function relating (d_{50}) to the resistance of the filtering medium (R_m). This equation (Eq. 11) was derived from Equation (1), proposed by Massarani (1997). A value of K=0.066 was obtained for the metallic cyclone.

The variations produced in parameter K by the permeabilities of the filtering medium can be incorporated in Equation (11) by multiplying K by function f(R_mD_c). This function should be equal to 1.0 for the filtering medium with infinite resistance (metallic cyclone) and increase with reduction in the value of this resistance.

$$\frac{d_{50}}{D_c} = 0.066\left[\frac{\mu D_c}{Q(\rho_s - \rho)}\right]^{0.5}\left(1 + \frac{A}{(R_m D_c)^B}\right) \qquad (11)$$

The values of the parameters obtained above for the equation were $A=2.28 \cdot 10^9$ and B=1.15 for a correlation coefficient of R=0.82. The ranges of validations for the following intervals are $32000 < Re < 80000$ and $2.4 \cdot 10^8 < R_mD_c < 4.5 \cdot 10^8$.

Figure 7 shows the fitted surface for the experimental values of Q and R_m. It can be observed that cut size decreases when flow rate and (R_mD_c) increase. A possible explanation for an increase in cut size with reduction in resistance of the filtering medium can be attributed to an alternative flow, produced through the conical filtering surface. This new passage of air can cause the centrifugal force inside the cyclone to decrease.

Table 2: Experimental results.

Cyclone R_m (m^{-1})	Q (m^3/s)	$\bar{\eta}$ (%)	ΔP (Pa)	Eu (-)	d_{50} (μm)
M ($R_m \rightarrow \infty$)	0.031	72.4	180	286	2.4
	0.054	73.6	570	302	1.9
	0.066	75.1	920	320	1.7
	0.076	75.9	1263	331	1.5
PE (R_m= 2.34 x 10^9)	0.031	67.9	156	252	2.7
	0.054	68.8	529	279	2.5
	0.066	71.9	830	290	2.3
	0.076	72.8	1097	291	2.1
PP (R_m=1.98 x 10^9)	0.031	66.3	176	266	2.9
	0.054	68.2	529	273	2.6
	0.066	69.6	815	285	2.4
	0.076	70.7	1087	280	2.1
PA (R_m=1.25 x 10^9)	0.031	63.5	137	219	3.5
	0.054	65.7	460	245	3.0
	0.066	67.7	730	257	2.7
	0.076	68.4	960	256	2.6

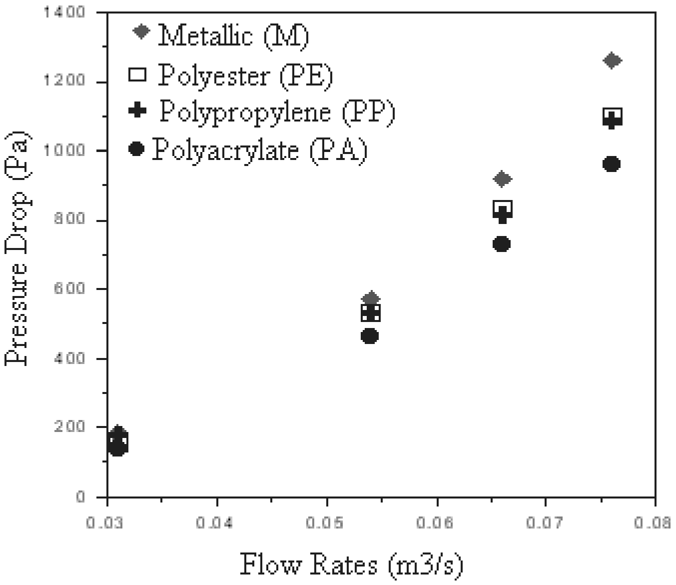


Figure 6: Pressure drop in the cyclone as a function of flow rate.

Table 3: Parameters of the cyclone configurations.

Cyclone	K [ ]	Eu [ ]	R_m (m^{-1})
M	0.066 ±0.004	310 ±24	∞
PE	0.087 ±0.006	280 ±28	2.34 x 10^9
PP	0.093 ±0.005	270 ±10	1.98 x 10^9
PA	0.104 ±0.005	240 ±21	1.25 x 10^9

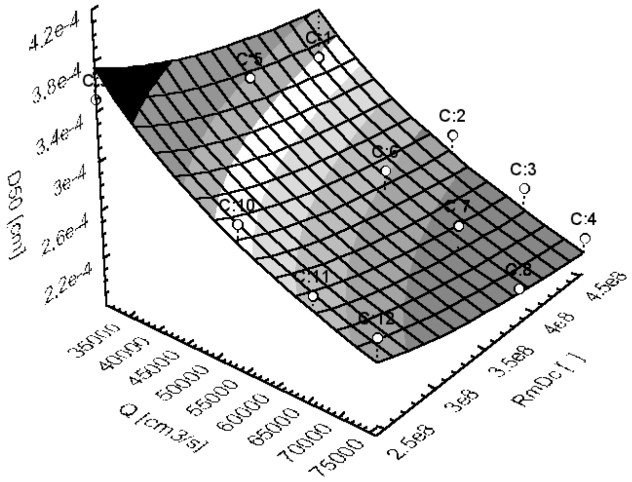


Figure 7: The fitted surface for d_{50} as a function of Q and of the adimensional (R_mD_c).

CONCLUSIONS

The experimental results obtained in this work show the following:

The Euler numbers for the cloth cyclones were always smaller than those for the conventional cyclone, indicating filtering with smaller pressure drops. The Euler number decreases when resistance of the filtering medium decreases.

The cut sizes obtained for the cloth cyclones were bigger than those for the conventional cyclone, indicating the lower separation efficiency of fine particles. A possible explanation for this phenomenon is the suspension current change in external from to the intern vortex, producing turbulence and dragging of solids in the overall current. This mixed effect is more pronounced for more permeable filtering media.

During the experiments with cloth cyclones there was no formation cake growth.

An equation was obtained that allows estimation of cut size diameters as a function of the properties of the solid-gas system, the operational conditions and the resistance of the filtering medium, where 67% of data variability were explained for this equation.

NOMENCLATURE

Dc	diameter of the cylindrical body of the cyclone	[L]
D_{inf}	internal lower diameter of the filtering cone	[L]
D_o	overflow tube diameter	[L]
d_{50}	cut size	[L]
Eu	Euler number	[-]
Gm	mass flow rate	[M/T]
K	design parameter in Eq. (1)	[-]
K_m	permeability of the filtering medium	$[L^2]$
L	length of the hydrocyclone	[L]
Lc	length of the cylindrical section of the hydrocyclone	[L]
Q	volumetric flow rate of the feed	$[L^3/T]$
R_m	resistance of the filtering medium	[1/L]
Re	Reynolds number	[-]
u	velocity of the gas in the input of the cyclone	[L/T]
u_c	average velocity in the cylindrical section of the cyclone	[L/T]
X	cumulative mass fraction	[-]
ΔP	pressure drop in the cyclone	$[M/LT^2]$

Greek Letters

η	individual efficiency of separation	[-]
$\bar{\eta}$	overall efficiency of separation	[-]
μ	gas viscosity	[M/(LT)]
ρ_s	solid density	$[M/L^3]$
ρ	gas density	$[M/L^3]$

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