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(54) **High efficiency cyclones**

(57) The present invention concerns high efficiency reverse flow cyclones - with a tangential entry of essentially rectangular section, sides a and *b*, the first parallel to the cyclone axis; a body of height *H*, with an upper cylindrical section of diameter D and height h and a lower inverted cone with smaller base of diameter D_b: and a cylindrical vortex finder of diameter D_e and length *s* - which may be used in laboratory or industrial conditions, whenever dedusting is needed.

The inventor could obtain an empirical correlation to estimate particle turbulent diffusivities under cyclone flow, through the use of a finite diffusivity theory which was adjusted to laboratory, pilot-scale and industrial grade efficiency curves. This correlation allows the design of reverse-flow cyclones of arbitrary geometry, as a function of particle size distribution and operating conditions. A computer program was made to obtain optimum designed reverse-flow cyclones, and two geometries have been obtained, which respectively maximise collection efficiency and one ratio efficiency/costs.

The proposed geometries, defined as ratios of the above mentioned dimensions to the cyclone inside diameter, differ from all geometries available in the literature, both being significantly more efficient. For flow rates typical of industrial multicyclones, the emissions should be 30-45% lower for the first family and 20-35% for the second, as compared with emissions from high efficiency cyclones available. Laboratory-scale tests with a similar geometry have confirmed the expected emissions reductions, at similar levels of pressure drop.

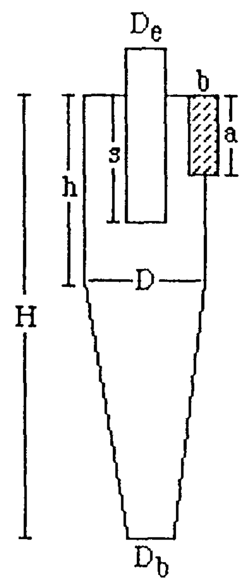

Fig. 1

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Description

Technical Area

[0001] The present invention, concerning cyclones, fits into the technical area of dedusting equipment.

[0002] As a matter of fact, cyclones are dedusters employed in a variety of industries, with two complementary objectives: dust removal from gases emitted from industrial processes, before release to the atmosphere (e.g. flue gas cleaning), and dust recovery of raw materials used in various processes (e.g. wood, cork, ferrous and non-ferrous industries).

State of the Art

[0003] Industrial cyclones are of various types, but the most widely used are reverse-flow cyclones, such as shown in Fig.1. The gas enters through the rectangular section *ab* and describes a descending spiral, eventually changing the direction of movement due to the established pressure field (thus the name 'reverse-flow') exiting through the vortex finder of length s and diameter D_e. During its descending path, the heavier (larger or denser) particles are swept to the cyclone wall and end up in the cyclone bottom, where they are separated from the gas.

[0004] Cyclone makers specify their designs through 'families', which are characterised by fixed relations of 7 key dimensions (the ratios of *a*, *b, s*, D_e, *h, H* and D_b relative to the inside diameter *D*).

[0005] Although the first cyclones date back to the XIX century, only recently can one use a theory of cyclone collection that may be confidently employed to design reverse flow cyclones. Thus theory adjusts well many data on grade-efficiency curves obtained both under laboratory and pilot or industrial scales, and was developed by Mothes and Loffler (1988), which will be from now on named ML theory. Its great disadvantage is that it could only be used as a diagnostic tool (viz. fitting data collected from available cyclones) and not as a prognostic tool (predicting cyclone behaviour for arbitrary geometries, operating conditions and particle size distributions). The problem lies in the lack of knowledge on the value of the particles turbulent diffusivity, a fundamental parameter in the ML theory, and on how it is affected by cyclone geometry, operating conditions and particle size distribution.

[0006] Some researchers have studied this problem, including the proponent (Clift et al., 1991; Salcedo, 1993, 1996; Salcedo and Fonseca, 1996). However, up to recently (Salcedo and Coelho, 1999), this parameter could not be described through any relation useful for cyclone designing.

[0007] Accordingly, the problem of improved cyclone design has been tackled by an empirical venue, as demonstrated by the few works related to the subject and available in the literature (Li et al., 1988; Schmidt, 1993). Although improved designs can be obtained by an empirical approach, the improvements are not very significant, further requiring an appreciable effort in development time.

[0008] Summarising, there is no guarantee, quite the contrary, that the best reverse-flow cyclones are available in the market, e.g., those with the highest possible efficiencies and simultaneously with reduced investment and operating costs. Cyclone makers go on today designing cyclones based mainly on their experience and empirical knowledge.

[0009] A more detailed comparison between the herein proposed geometries and those based on the state of the art, namely the geometry related to EP0564992 and other 9 geometries available from a literature survey, will be made below, both in the final part of the Description of invention as well as in the chapter on Practical examples.

A new approach

[0010] With the objective of obtaining reverse-flow cyclones which exhibit significantly enhanced efficiencies over those of competing high-efficiency cyclones available, a study was first made on the applicability of the ML theory to grade efficiency curves (collection efficiency vs. particle size) of 21 literature cases. The cyclones' diameters varied from 0.03658 to 0.305m and the gas flow rates from 0.7 to 835Nm3h-1, corresponding to both laboratory and to pilot or industrial scales. The adjusted turbulent diffusivities were next correlated with particle size, cyclone geometry and operating conditions. After a considerable effort, an empirical correlation that is statistically significant at a 95% confidence level, and which explains 70% of the observed data variance, could be obtained. This correlation can be employed with confidence for the design of new geometries of the reverse-flow type, and is given by (Salcedo and Coelho, 1999):

$$Pe = A.Re^{B} \tag{1}$$

where (*A,B*) are two appropriate constants, *Pe* is the non-dimensional Peclet number, which depends on the particles' turbulent diffusivity, and *Re* is the non-dimensional Reynolds number, which depends on cyclone geometry and operating conditions. The operating conditions, when coupled to the ML theory and to the cyclone geometry, give the corresponding value for *Re.* From correlation (1), the value of *Pe* is then obtained, which then gives directly the corresponding value for the particles' turbulent diffusivity. The use of the proposed correlation gives much better results than using a constant value for the diffusivity, as some authors do (Clift et al., 1991; Hoffmann et al., 1996) or by using different correlations proposed in the literature (Ogawa, 1984, 1987; Li and Wang, 1989).

[0011] In a second phase, a computer program was developed to optimise the cyclone geometry, based on two distinct criteria: maximum efficiency and maximum ratio efficiency/costs. For this second criterion, the investment and operating costs were estimated by maximising a non-dimensional parameter K_{Licht}, proposed by Licht (1980). The computer program uses the ML theory with the estimated diffusivity obtained from correlation (1), and optimises the cyclone geometry using a non-linear optimiser available (Salcedo, 1992). Several constraints were imposed on the optimisation, such as geometric criteria, to obtain feasible cyclones, and maximum pressure drop criteria, to obtain cost effective designs. The maximum pressure drop was set at 1500 Pa (≈150mm w.g.), as these are usual values in high-efficiency cyclones for industrial applications. A constraint on saltation velocity was also included, using the criterion of Kalen and Zenz (Licht, 1980), so that the optimised designs correspond to cyclones where saltation is small or absent (emission to the atmosphere of reentrained particles). Thus, the optimised designs should have collection efficiencies close to the design targets.

[0012] Since the results obtained from the optimiser in the second phase produced geometries that varied with the operating conditions, it was necessary to conduct further simulations to obtain a single geometry for each of the two optimisation criteria previously considered (maximum efficiency and maximum ratio efficiency/cost). After hundreds of simulation-optimisation runs, similar geometries could be detected for each of the two optimisation criteria. These define two cyclone geometries, from now on designated as cyclones (A) and (B).

Description of invention

[0013] High efficiency reverse flow cyclones as per the invention - which comprise a tangential entry of essentially rectangular section, of sides a and *b*, the first parallel to the cyclone axis, as well as a body of height *H,* with an upper cylindrical body of diameter *D* and height *h,* with a lower inverted cone with bottom base of diameter D_b, as well as a cylindrical vortex finder of diameter D_e and length *s* - with geometries obtained as described above, are characterised, respectively for both geometries A or B (the first relative to maximum efficiency cyclones and the second to cyclones with a maximum value for the parameter K_{Licht}, e.g., the ratio efficiency/cost) as having the aforementioned sides, heights and diameters interrelated so that the ratios of the corresponding internal dimensions to the cyclone internal diameter are between the non-dimensional values listed in the first seven lines of Table 1.

[0014] Such table, given below, besides showing the seven ratios of the key dimensions cited above, has two additional lines: one relative to the non-dimensional cone height *(H/D - h/D)* and the other relative to the efficiency/cost ratio K_{Licht}.

Tab.1 -

Geometries of optimised cyclones		
Ratio	Cyclone A	Cyclone B
a/D	0.270-0.360	0.270-0.310
b/D	0.270-0.360	0.270-0.310
s/D	0.330-0.495	0.330-0.395
D_e/D	0.280-0.370	0.405-0.430
h/D	1.001-1.300	2.050-2.260
H/D	4.050-4.250	3.500-3.700
D_b/D	0.200-0.300	0.250-0.300
(H-h)/D	2.750-3.250	1.240-1.650
K_{Licht}	59.0	124.7

[0015] To verify that the proposed geometries are very different from those available in the marketplace, Table 2 shows the same ratios as given in table 1, for various known geometries.

Table 2 -

Geometries of cyclones available in the literature									
Ratio	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
a/D	0.544	0.500	0.500	0.750	0.500	0.440	0.500	0.583	0.635
b/D	0.306	0.230	0.200	0.375	0.250	0.210	0.250	0.208	0.279
s/D	0.544	0.654	0.500	0.875	0.625	0.500	0.600	0.583	0.500
D_e/D	0.500	0.523	0.500	0.750	0.500	0.400	0.500	0.500	0.583
h/D	0.544	0.654	1.500	1.500	2.000	1.400	1.750	1.333	1.750
H/D	2.988	3.165	4.000	4.000	4.000	3.900	3.750	3.170	3.850
D_b/D	0.500	0.317	0.375	0.375	0.250	0.400	0.400	0.500	0.400
(H-h)/D	2.444	2.511	2.500	2.500	2.000	2.500	2.000	1.837	2.100
K_{Licht}	9.04	24.33	46.94	1.73	25.45	41.21	25.10	27.57	10.25

[0016] The nine cyclones of Table 2 are identified in Table 3

Table 3 -

Identification of cyclones from Table 2	
Cyclone	
1	Almeida (1980) - cyclone for boiler flue gas cleaning
2	Li et al. (1988) - cyclone Zhou#8, empirically optimised
3	Licht (1980) - cyclone Stairmand HE
4	Licht (1980) - cyclone Stairmand HT
5	Licht (1980) - cyclone Lapple
6	Licht (1980) - cyclone Swift HE
7	Licht (1980) - cyclone Swift GP
8	Licht (1980) - cyclone Petterson-Whitby
9	High efficiency cyclone commercialised in Portugal

[0017] By comparing the values from Tables 1 and 2, cyclone A has all the ratios of the seven key dimensions different from all other cyclones, except in three cases, where, even so, the differences are enormous since only one ratio is common to some other geometry, while the six remainder are all different. For cyclone B, the situation, in number, is exactly the same.

[0018] The main characteristics that distinguish the optimised geometries from the other geometries, and which may be read from the tables, are :

- gas entry preferably through a square section and not a rectangular one;
- vortex finder has smaller diameter (lower D_e/D) and cone is higher (larger H/D-h/D) in cyclone A;
- cylindrical body taller (larger h/D) and cone shorter (lower H/D-h/D) in cyclone B;
- larger value for the efficiency/cost ratio K_{Licht}.

[0019] On the other hand, to show that the proposed geometries are quite different from that corresponding to the cyclone design described in document EP0564992 - from now on designated as cyclone 10 - the corresponding ratios of Table 1 are given for this geometry in Table 4:

Table 4 -

Geometries of cyclones EP0564992	
Ratio	(10)
a/D	0.274-0.500
b/D	0.141-0.258
s/D	0.270-0.750

Table 4 - (continued)

Geometries of cyclones EP0564992	
Ratio	(10)
D_e/D	0.300-0.700
h/D	0.160-1.000
H/D	0.800-2.000
D_b/D	> 0.640
(H-h)/D	< 2.551
K_{Licht}	80

[0020] Comparing the corresponding values in Tables 1 and 4, it is seen that both cyclones A and B have four out of the seven ratios of the key dimensions completely different from cyclone 10. Also, cyclone A has two of the remainder ratios partially different from those of cyclone 10, while cyclone B has one.

[0021] The main characteristics that distinguish the proposed geometries from cyclone 10, among others that may be inferred from Tables 1 and 4, are the following:

- gas entry preferably through a square section and not a rectangular one;
- cone is higher (larger H/D-h/D) in every cyclone A, and vortex finder has smaller diameter (lower D_e/D) in part of them;
- cylindrical body taller (larger h/D) and larger value for the efficiency/cost ratio K_{Licht} in cyclone B

[0022] On the other hand, cyclone B relative to cyclone A is characterised by a common trait for the both first three ratios and the last ratio of the key dimensions, since the interval limits for cyclone B are within the interval limits for cyclone A. Furthermore, since the first two ratios are identical, for each cyclone type, this shows that the two geometries share some common gas entry characteristics.

[0023] Thus, the present patent request refers to two reverse-flow cyclone geometries, which were optimised by computer, with geometrical characteristics very different from cyclones available in the marketplace and being both significantly more efficient. Cyclone A is the most efficient while cyclone B, with a somewhat lower efficiency, has also correspondingly lower pressure losses and investment and operating costs.

Brief description of figures

[0024]

Figure 1 represents a typical reverse-flow cyclone, with the corresponding key dimensions;

Figure 2 represents a scaled version of the first 8 cyclones in Table 2, for an arbitrary diameter of 0.02m, where the entries of the first and fourth cyclone are wrap-around, and the other are helical;

Figure 3 compares the experimental and predicted grade-efficiencies for cyclone A and cyclone 3 (Table 2), at a laboratory-scale. The operating conditions were: flow rate 0.9 m^3h^{-1}, mean mass diameter 1.37 μm;

Figure 4 compares global collection efficiencies for cyclone A and various cyclone geometries represented in Figure 2 (namely cyclones 2, 3, 6 and 8), for varying flow rates. The operating conditions were: mean mass diameter 3.67 μm;

Figure 5 is identical to Figure 4, for the same operational conditions, but refers to cyclone B instead of cyclone A.

Figure 6 shows, for the same arbitrary diameter as Figure 2, and also at scale, an example of a cyclone A and another of a cyclone B.

Practical examples

[0025] Six minicyclones with diameters ranging from 0.0215 to 0.07m were built to confirm experimentally the expected behaviour. Three were of the Stairmand HE type (cyclone 3 in Table 2 and in Figure 2), while the other three were optimised. For all cases, a substantial increase in efficiency was observed.

[0026] Figure 3 shows the behaviour of two minicyclones, respectively cyclone A, and the other, cyclone 3 as referred. This figure shows the experimental grade efficiencies (shown by white dots for cyclone A and by black dots for cyclone 3), and also, for both cyclones, the expected grade efficiencies from the ML theory when coupled with the estimates of turbulent diffusivity given by correlation (1). These are represented by a discontinuous curve for cyclone A and by a continuous curve for cyclone 3. The test dust is ultra fine, since it has a mean mass diameter of 1.37 μm (it is the mass distribution that matters since the emission legal limits refers to dust concentration on a mass basis). The global efficiencies, which are weighted averages of the grade efficiencies taking into account the particle size distribution, were respectively of 38% and 55% for cyclones 3 and A, viz. the penetration through the optimised cyclone was 27% lower in comparison with the Stairmand HE cyclone.

[0027] The expected cyclone behaviour under industrial conditions may be seen from Figures 4 and 5, which compare, for a very fine dust (mean mass diameter of 3.67 μm), the expected collection for the two optimised families A and B with those from four high-efficiency geometries (Licht, 1980; Li et al., 1988). The increase collection of the optimised geometries is significant. For flow rates between 100-200 Nm^3h^{-1}, typical of industrial multicyclones (small diameter cyclones, in parallel), the expected penetrations from geometry A are about 30-45% lower than from the high efficiency Swift HE and Stairmand HE cyclones, respectively (Figure 4). For geometry B, the expected penetrations are 20-35% lower (Figure 5).

[0028] Comparing now the predicted behaviour of cyclone 10 (EP0564992) with the proposed geometries, for the same type of dust referred in Figure 4, and, for example, with a flow rate of 110 m^3h^{-1}, typical of industrial multicyclones, while the global efficiency for cyclone A is 92.5%, as can be seen from Figure 4, that for cyclone 10 is between 65% and 78%, depending on whether its dimensioning is made considering the maximum allowable inlet velocity to avoid saltation, or not. Clearly, cyclone 10 is not a high-efficiency design.

[0029] Thus, it is expected that the optimised geometries may significantly reduce the penetrations in comparison with other high efficiency designs, at comparable pressure drop and saltation (reentrainment) effects. These conclusions are in agreement with the experimental data observed under laboratory conditions.

[0030] The development of cyclones with collection efficiencies significantly greater than those currently available in high efficiency designs, especially for particle sizes around 2-3 μm, has a good potential for industrial applicability. Several industries (wood processing, ferrous and non-ferrous, cement, chemical production in powder or granulates, fertilisers) as well as simply for flue gas cleaning could benefit from low cost equipments with sufficient collection efficiency to avoid the use of much more expensive equipment, such as electrostatic precipitators and bag filters. Even if the legal limits may only be enforced with the use of electrostatic precipitators and bag filters, the use of very high efficiency cyclones as primary collectors could be easily justified on the grounds of the protection they would bring to the more expensive equipments. Furthermore, in the case of very high temperatures, cyclones are currently the only available means of dust collection.

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Claims

1. High efficiency reverse flow cyclone - with a tangential helical entry of essentially rectangular section, sides *a* and *b,* the first parallel to the cyclone axis; a body with an upper cylindrical body of diameter *D* and height *h* and a lower inverted cone with base diameter D_b; and a cylindrical vortex finder, of height *s* - characterised by interrelations between the sides, heights and diameters such that the ratios of the corresponding internal dimensions to the internal cyclone diameter *D* belong to the following non-dimensional intervals :

a/D	0.270-0.360
b/D	0.270-0.360
s/D	0.330-0.495
D_b/D	0.200-0.300

2. Reverse flow cyclone - with a high efficiency, as per previous claim, with a body of height *H,* with an upper cylindrical body of height *h* and a cylindrical vortex finder of diameter D_e - characterised by having its geometry defined, additionally, in terms of the ratios of heights and diameter to the corresponding internal cyclone diameter *D,* by the following non-dimensional intervals :

D_e/D	0.280-0.370
h/D	1.001-1.300
H/D	4.050-4.250

3. Reverse flow cyclone - with a high efficiency, as per the first claim, with a body of height *H,* with an upper cylindrical body of height *h* and a cylindrical vortex finder of diameter D_e - characterised by having its geometry defined, additionally, in terms of the ratios of heights and diameter to the corresponding internal cyclone diameter *D,* by the following non-dimensional intervals:

D_e/D	0.405-0.430
h/D	2.050-2.260
H/D	3.500-3.700

and in terms of the ratios as per the first claim, by the following subgroups:

a/D	0.270-0.310
b/D	0.270-0.310
s/D	0.330-0.395
D_b/D	0.250-0.300

4. Cyclone as per any of the previous claims, characterised by the sides *a* and *b* being equal, with a square entry section.

5. Cyclone as per claim no.3, characterised by a wrap-around tangential entry.

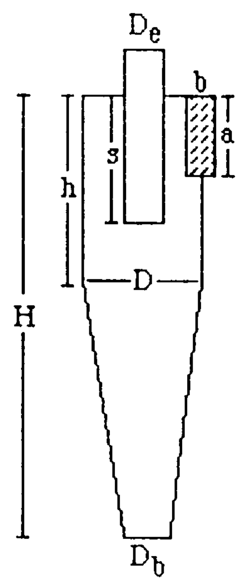


Fig. 1

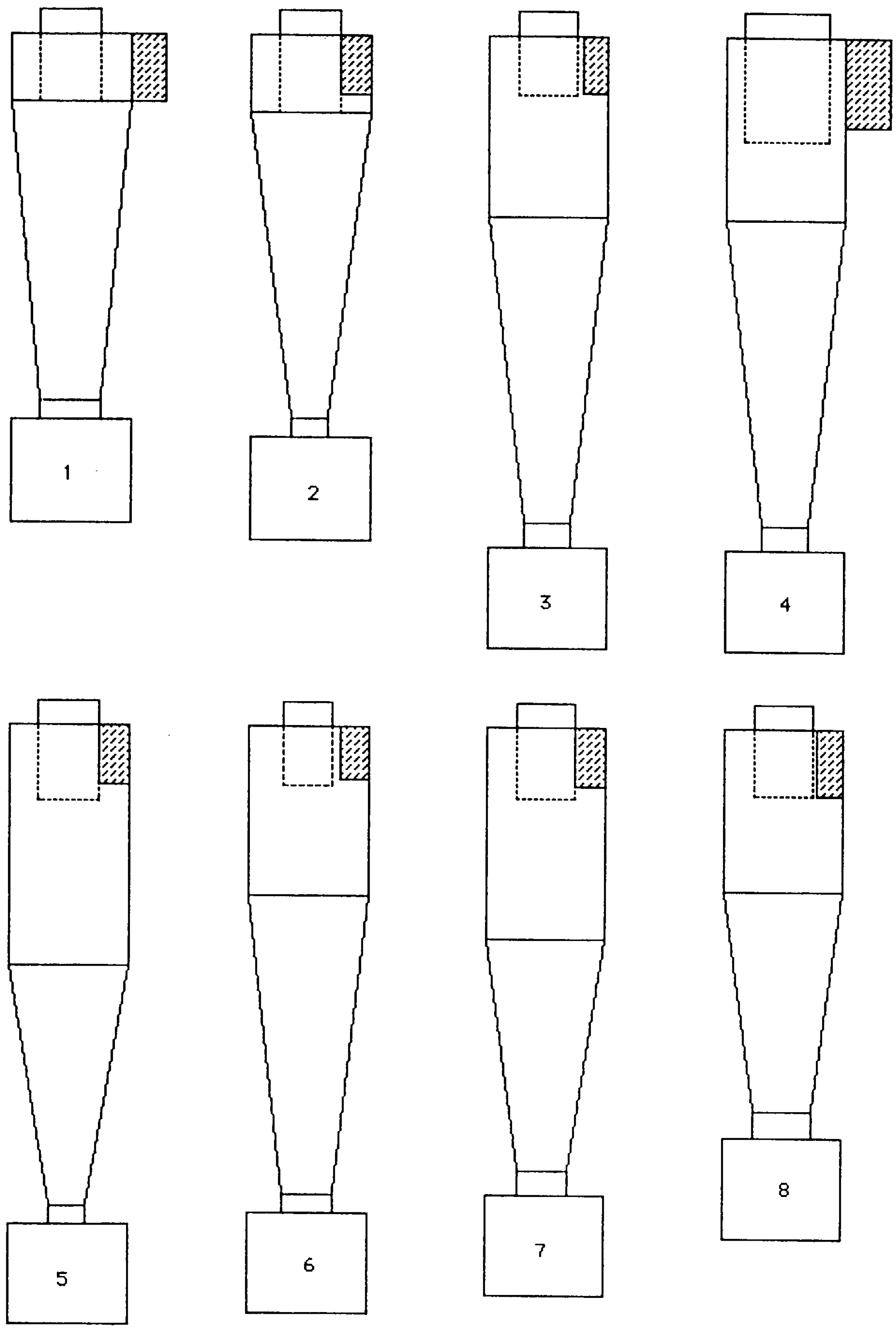
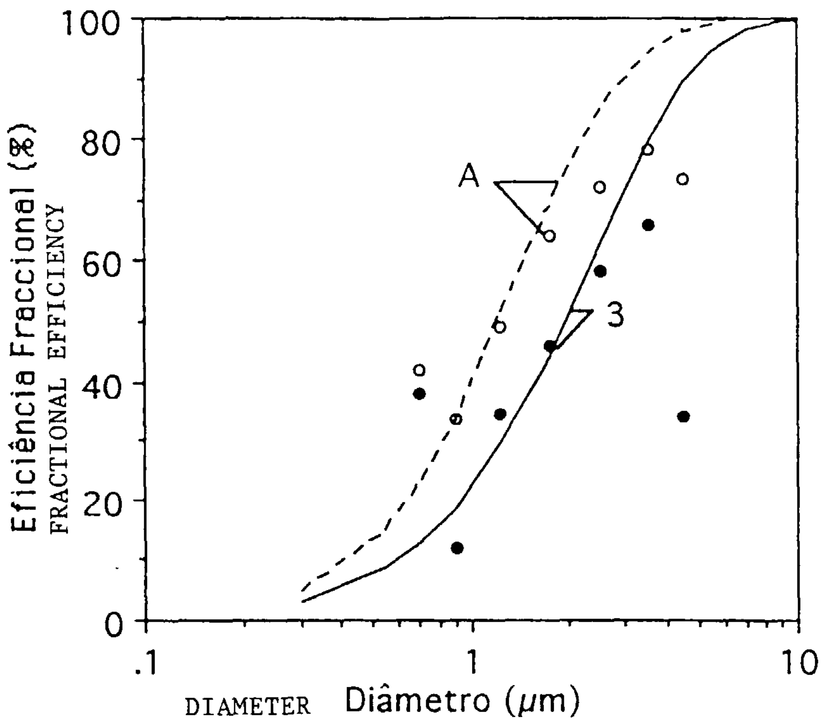


Fig.2


100
80
60
40
20
0
.1
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Eficiência Fraccional (%)
FRACTIONAL EFFICIENCY
DIAMETER
Diâmetro (μm)
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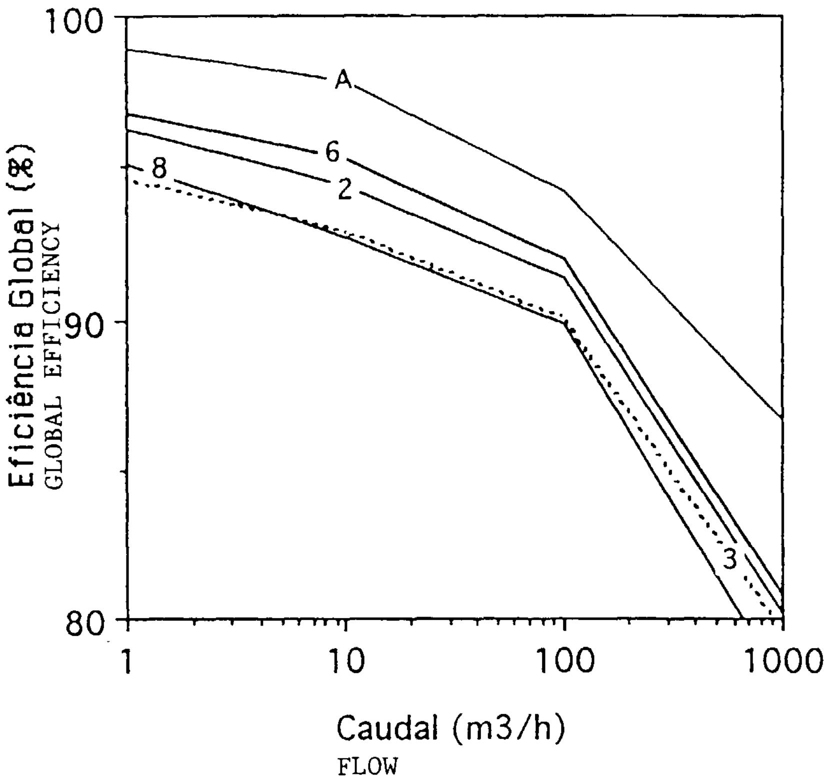
3

Fig. 3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Eficiência Global (%)
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Caudal (m3/h)
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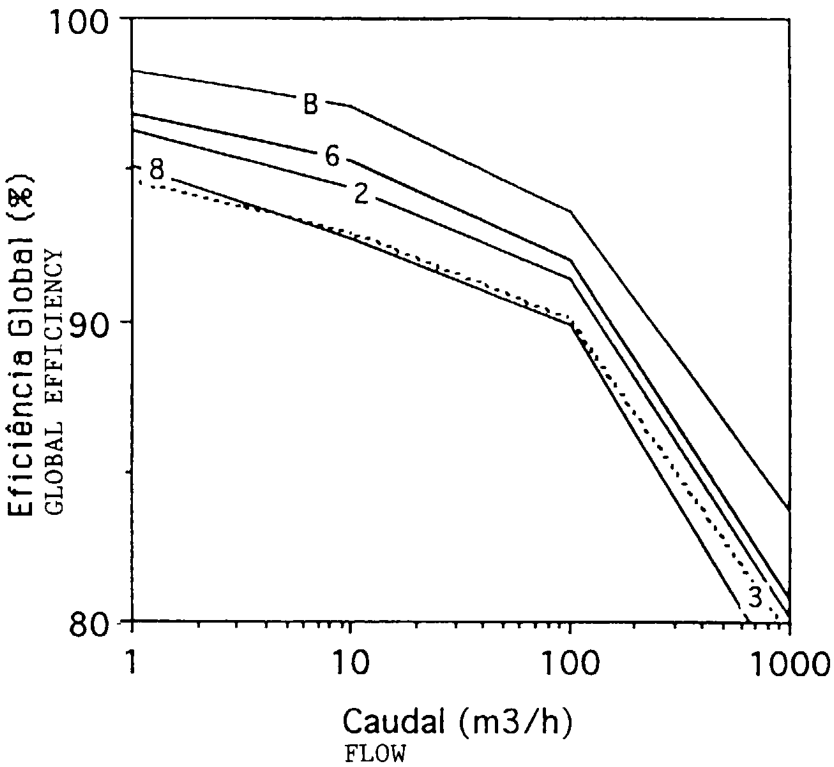
Fig. 4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Caudal (m3/h)
FLOW

Fig. 5

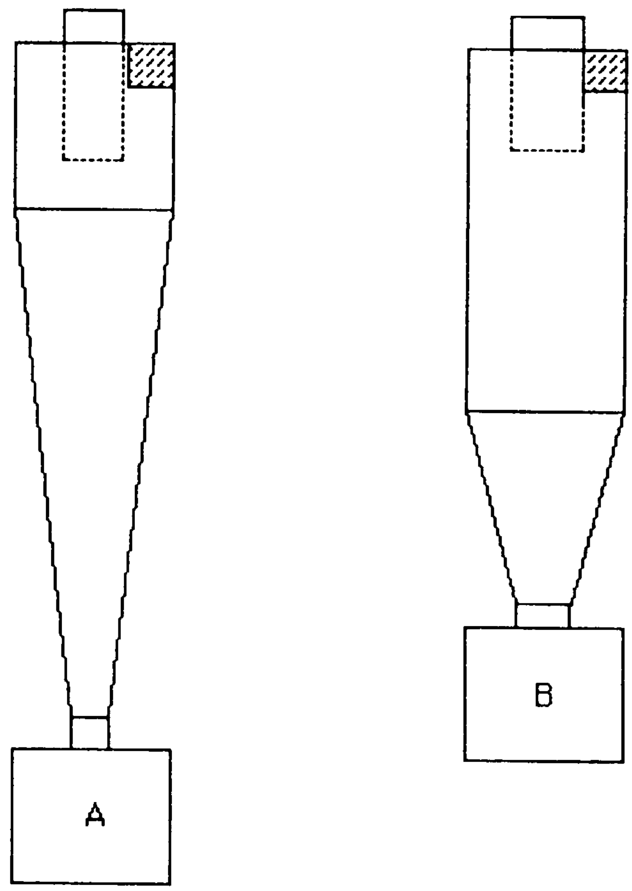

Fig. 6