

Laboratory, pilot and industrial-scale validation of numerically optimized reverse-flow gas cyclones

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Abstract

This paper addresses the experimental validation of the optimum design of reverse-flow gas-cyclones, obtained through the solution of a numerical non-linear optimization problem, viz. maximizing cyclone collection. The simulation model is based on the predictive properties of a finite diffusivity model, where the particles' turbulent dispersion coefficient is estimated through an empirical correlation between the radial Peclet and Reynolds numbers. The optimizations were formulated with constraints on pressure drop, saltation velocity and geometrical considerations, such that feasible cyclones could always be obtained.

The optimum geometry, named RS_VHE, is different from available high-efficiency designs, and represents reverse-flow cyclones with a predicted significantly improved performance. An innovative partial recirculation system within a collector-first arrangement further reduces emissions with only a moderate increase in pressure drop. The generally observed unexpected high collection of submicron particles is attributed to capture by larger particles in the turbulent flow field due to turbulent dispersion, much like what occurs in re-circulating fluidized beds.

Results obtained for the RS_VHE cyclones with partial recirculation at laboratory, pilot and industrial scales, for temperatures ranging from 300 to 600 K, gas flow rates from 1 to 10⁴ m³/h and inlet loads from 15 to 10⁴ mg/m³, show them to be significantly more performing than equivalent diameter HE cyclones or smaller diameter multi-cyclones. Under certain circumstances, with recirculation the proposed system shows better performance than on-line pulse-jet bag-filters.

Overall, the results show that the numerically optimized RS_VHE cyclones, when coupled with a partial recirculation system, open the applicability of these simple devices for fine particle collection which is typical of more expensive devices, such as venturis and on-line pulse-jet bag-filters.

KEYWORDS : optimized gas cyclones, recirculation, turbulent dispersion, fine particle, pilot plant, industrial practice

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Introduction

Cyclones are gas-solid separation devices used in a wide variety of industries, mainly with three purposes: for the recovery of raw or process material, as collectors for compliance with particulate emission limits, and as primary collectors for reducing the burden on more expensive secondary collectors, such as bag-filters and electrostatic precipitators. The development of cyclones with very high efficiencies, especially for fine particles below $2\text{-}3\ \mu\text{m}$ in particle diameter, could have a significant impact in the chemical processing industries¹. This is especially relevant in some cases of operation at high temperature and pressure, where cyclones are actually the only available de-dusters. The drawback of considering a cyclone solution to an air emission problem is that a thorough study of each case is necessary², but this extra work may eventually pay, since properly designed cyclones are essentially free of maintenance costs¹.

The main design of industrial gas cyclones is the tangential reverse-flow type, depicted in Fig.1.

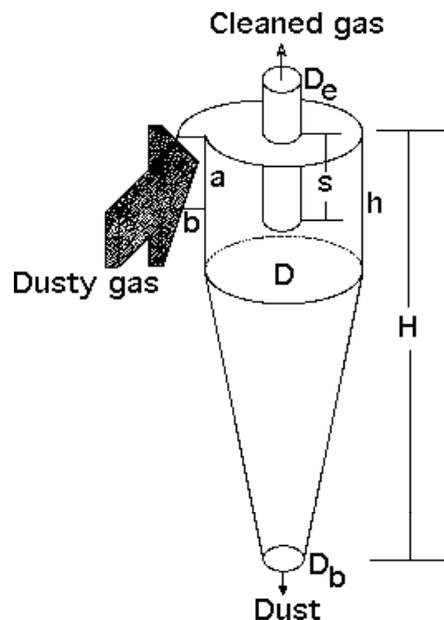


Fig. 1 – Reverse-flow gas cyclone

The gas enters tangentially through the section ab near the top, and describes an outer descending vortex, which changes into an inner ascending vortex through the vortex finder of length s and diameter D_e . While descending with the gas, the particles are swept to the walls by a centrifugal field and eventually drop out to the cyclone bottom. This simplified picture is usually perturbed by several non-ideal phenomena, such as secondary flows and particle re-entrainment.

Obtaining high efficiency cyclones has been essentially an empirical task. However, due to the dimension of the problem (an 8-degree of freedom problem for a single cyclone, with 4 axial and 4 radial dimensions), cyclone improvement through empirical design has been at best moderately succeeded.

The present work refers to the performance evaluation of numerically optimized reverse-flow gas cyclones (RS_VHE geometry), which were designed by solving a numerical optimization problem^{3,4,5,6,8}. In parallel, a recirculation system within a collector-first approach has also been implemented⁶, which brings the RS_VHE cyclone efficiencies to values which are typical, under certain circumstances, of on-

line pulse-jet bag-filters. These systems have been studied at laboratory^{3,8} ($\approx 1 \text{ m}^3/\text{h}$), pilot⁶ ($\approx 1000 \text{ m}^3/\text{h}$) and industrial⁶ ($\approx 10000 \text{ m}^3/\text{h}$) scales.

This paper shows at laboratory-scale that cut-points of 0.3-0.4 μm can be achieved with very fine inlet distributions. Collection efficiencies close to 100% were obtained for 1 μm particles, even when operating at extremely low inlet concentrations ($\approx 15\text{-}20 \text{ mg}/\text{m}^3$), in order to avoid higher collection due to fine particle capture by turbulent dispersion agglomeration⁷. Results for two full-scale facilities built to replace a multi-cyclone bank for the capture of fine soot emitted from a corch waste boiler and an on-line pulse-jet bag-filter for the recovery of sulphanilic acid are also shown.

Numerical optimization of reverse-flow gas cyclones

The numerical optimization of reverse-flow gas cyclones was made by using a finite diffusivity simulation model for particle capture under cyclone flow⁹, with the particles' turbulent dispersion coefficients obtained through an empirical relation between the radial Peclet and Reynolds numbers. This estimate predicts grade efficiency curves that agree reasonably well with the experimental data from various authors, and is given by²:

$$Pe_p = 0.0342 Re_p^{1.263} \quad (1)$$

where $Pe_p = u_r d_p / D_r$ is the radial particle Peclet number, D_r is the radial dispersion coefficient and $Re_p = \rho d_p u_r / \mu$ is the radial particle Reynolds number. The optimization was performed using an available stochastic adaptive random search global optimizer¹⁰.

To ensure feasible cyclones, several geometric constraints were imposed on the optimization problem. Constraints on maximum allowable pressure drop (1500 Pa) and that the solution to the optimization problem should not promote particle re-entrainment¹¹ were also enforced. Two different optimization criteria were used, namely maximizing efficiency or a ratio efficiency/cost¹¹, and two completely different geometries were obtained.

Details of the numerical optimization problem can be found elsewhere^{3,8}, and in this paper we examine the maximum efficiency cyclones (RS_VHE), which are described under patents PT102166 and EP0972572⁴.

Partial recirculation system

Apart from geometrical considerations, one way to increase cyclone collection efficiency is to promote partial recirculation with a straight-through cyclone concentrator. Our recirculation system differs from those available in the literature¹¹ and on the marketplace¹² since it locates the collector (reverse-flow cyclone) upstream of the concentrator (straight-through cyclone), as depicted in Fig. 2. This alternative sequencing, described in detail under patents PT102392 and WO0141934⁵ (US 2002/0178703 A1), has a global efficiency (η), which depends on the collector and concentrator efficiencies, respectively η_c and η_s , given by:

$$\eta = \frac{\eta_c}{1 - \eta_s + \eta_c \eta_s} \quad (2)$$

The system efficiency (η) will be higher than that of the reverse flow cyclone (η_c), since it is only required that $\eta_s(\eta_c - 1) < 0$, which is always verified. It can also be shown⁶ that the proposed system is always more efficient than the concentrator-first arrangement^{11,12}, as long as the individual in-loop efficiencies (collector and concentrator) are the same in both systems.

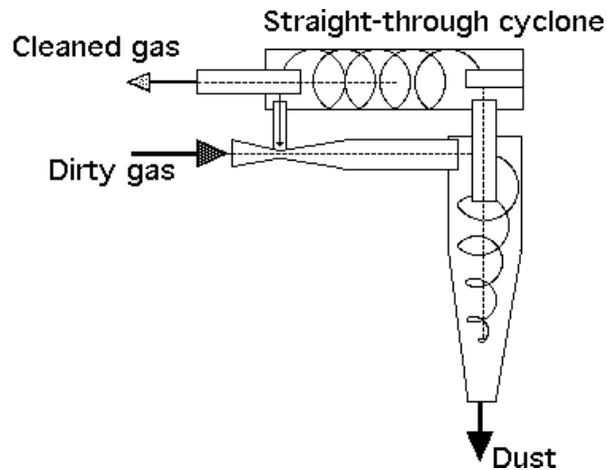


Fig. 2 – Proposed recirculation system

Laboratory-scale experiments

The laboratory-scale experiments were performed at ambient temperature on a variety of fine dusts using a 0.02 m diameter RS_VHE design, with and without recirculation. The performance of the tested systems in the absence of recirculation, as compared with Stairmand HE designs can be found elsewhere^{2,3,8}, where typically emissions are reduced by up to 50%.

Due to the very small flows involved ($\approx 1\text{ m}^3/\text{h}$), recirculation was achieved using a small ASME venturi¹³ (0.002 m throat diameter). Two different dusts were fed to the cyclone, namely CaCO_3 and fine glass.

Collection of CaCO_3

The CaCO_3 test dust has a median mass diameter of $3.17\ \mu\text{m}$, specific gravity $2745\ \text{kg}/\text{m}^3$, and was injected from a Wright dust feeder¹⁴ at a fixed air flow rate of $2.57 \pm 0.02 \times 10^{-4}\ \text{m}^3/\text{s}$ and inlet loads of $2152 \pm 53\ \text{mg}/\text{m}^3$. To avoid the presence of large agglomerates at the test cyclone inlet, a 0.07 m diameter Stairmand HE de-agglomerating cyclone was placed upstream of the test cyclone. Fig. 3 shows that all particles fed to the test cyclone are below $10\ \mu\text{m}$ in diameter, and that the recirculation system produces the finest emissions. It also shows that extremely fine particles have been removed by either the single RS_VHE or the recirculation system. Particle size distributions were analyzed off-line down to $0.04\ \mu\text{m}$ using a Coulter LS 230 laser sizer, after re-dispersion in ethanol with ultrasounds.

Fig. 4 shows the average grade-efficiency curves obtained with and without partial recirculation, where about 16% of the airflow was re-circulated. It is clear that very high collection efficiencies were obtained, even with inlet average air velocities as low as $8.2\ \text{m}/\text{s}$ (the fixed test velocity). The abnormal collection of very fine particles (below about $1\ \mu\text{m}$) had been observed before with the RS_VHE cyclones, with and without recirculation, at both pilot and full-scales for the capture of fine sulphanic

acid, and is attributed to capture of small particles by larger ones in the turbulent cyclone flow field⁶, much as it happens in re-circulating fluidized beds⁷.

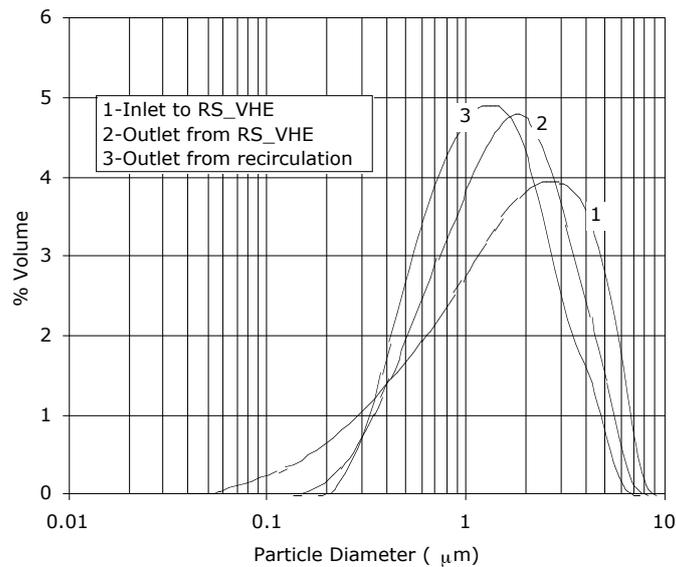


Fig. 3 – CaCO₃ distributions of the RS_VHE laboratory cyclone

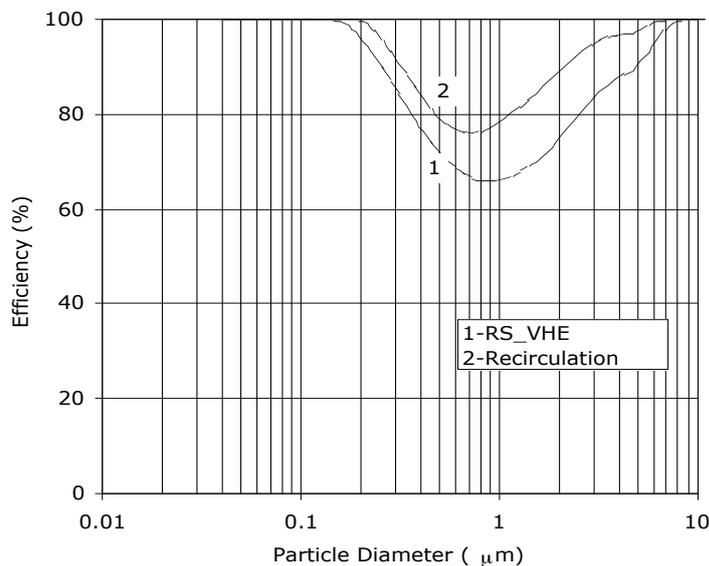


Fig. 4 – CaCO₃ grade collection efficiency for RS_VHE and recirculation

Collection of glass dust

For the glass dust experiments, only the recirculation system was tested and a different approach was used. The glass dust was also injected from the Wright dust feeder, but at a larger air flow rate of $3.84 \pm 0.07 \times 10^{-4} \text{ m}^3/\text{s}$, corresponding to an average cyclone inlet velocity of 12.3 m/s. Particle size distributions were measured on-line using a Grimm 1.108 dust monitor, down to 0.23 µm, and were varied by using a cascade of small sampling cyclones⁸. Table I gives the experimentally

observed inlet and outlet concentrations, global collection efficiencies and median mass diameters of the inlet and outlet distributions. This table shows that extremely small loads and fine inlet distributions could be achieved with the variable cascade of small cyclones located upstream of the test cyclone, and that the emissions from the recirculation system stabilize around 0.35 μm .

Table I – Experimental results for collection of glass dust

Inlet (mg/m^3)	Outlet (mg/m^3)	Efficiency (%)	Inlet d50 (μm)	Outlet d50 (μm)
15	3.34	77.75	1.14	0.35
18	2.78	84.57	1.32	0.38
21	2.99	85.78	1.60	0.38
25	2.72	89.14	1.78	0.38
59	1.91	96.77	2.44	0.38
108	3.25	96.99	2.76	0.39
196	3.55	98.19	3.40	0.45
557	3.45	99.38	5.28	0.52

Fig. 5 shows the average (\pm one standard deviation) of the grade-efficiency for all these experiments, where it can be seen that the predictions from the Mothes and Löffler model⁹, using an averaged value for the inlet distribution and an empirical estimate of turbulent dispersion², is in good agreement with the experimental data. This figure shows that cut-points of about 0.32 μm were obtained, and that the abnormal collection of fine particles is not observed at these very low loads.

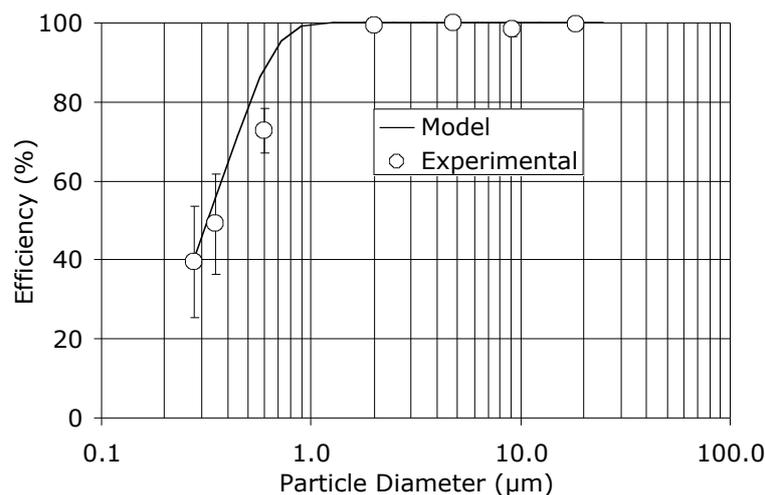


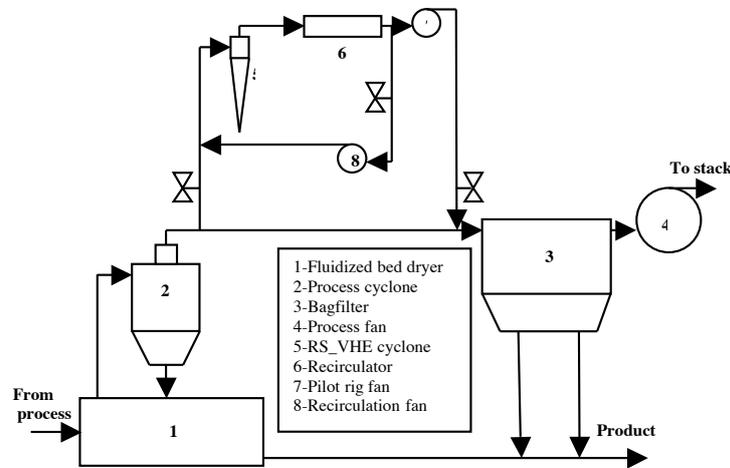
Fig. 5 – Grade efficiencies for the glass dust and model^{2,9} predictions

Pilot and industrial-scale experiments

Pilot-scale collection of sulphanilic acid

A pilot-scale test rig made-up by one 0.447 m diameter RS_VHE cyclone and concentrator was installed at the sulphanilic acid production facility of a Portuguese manufacturer of benzene derived organic chemicals. Basically, a fluidized bed dryer conveys sulphanilic acid dust to a 0.80m diameter high-loadings process cyclone that returns the bottom fraction to the dryer and the finer top fraction to a pulse-jet bag-filter, at a flow rate of about $10^4 \text{ m}^3/\text{h}$, temperature of 350K and concentrations

up to 20 g/m^3 . By installing the pilot rig in parallel with the bag-filter, about 10% of the flow could be diverted by a variable-speed induced fan to the pilot rig RS_VHE cyclone, fitted with the recirculation straight-through cyclone and corresponding variable-speed induced recirculation fan. The pilot-scale system was designed to handle up to $1000 \text{ m}^3/\text{h}$ of process gas and $500 \text{ m}^3/\text{h}$ of recirculation gas. Fig. 6 shows a schematic diagram of the pilot rig.



Comparison was also made with the performance of a competing high efficiency (HE) cyclone available on the marketplace and with an installed on-line cleaning pulse-jet bag-filter. The test results and HE cyclone geometry can be found elsewhere⁶, but the main conclusion can be seen in Fig. 7. These results are given in terms of penetrations (100 - % collection efficiency), since this amplifies relative differences for high collection efficiencies. For example, two de-dusters having collection efficiencies respectively of 98 and 99%, show a large relative difference in penetration (50%) but a marginal relative difference in collection (about 1%). The RS_VHE cyclone alone clearly outperformed the HE cyclone and the recirculation system outperformed the bag-filter.

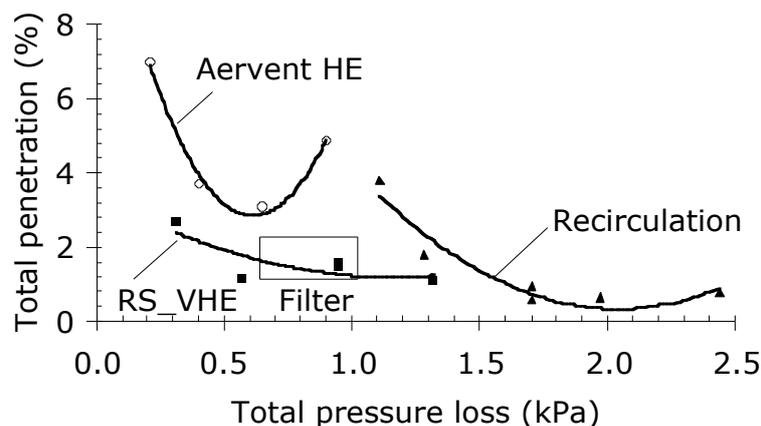


Fig. 7 – Global penetrations of pilot RS_VHE and recirculation for sulphanilic acid

Full-scale collection of sulphanilic acid and corch boiler fly ash

Based on the pilot experiments, two full-scale facilities have been built, one for the recovery of sulphanilic acid, replacing the on-line pulse-jet bag-filter (Fig. 7a) and the other for air pollution control at a corch waste (biomass) boiler, replacing a multi-cyclone bank (Fig. 7b).



Fig.7a –Sulphanilic acid cyclones



Fig.7b –Corch waste boiler cyclones

The sulphanilic cyclones have two banks of six 0.50 m diameter RS_VHE cyclones with one recirculator each, with a design flow rate of 14000 m³/h at 340 K, with loads that may reach 20 g/m³. The recirculation fraction is about 20%. The boiler RS_VHE cyclones are larger (0.70 m diameter) with a single recirculator, designed for 9500 m³/h at 600 K and 30% recirculation, but at much smaller loads (0.4 g/m³). Fig. 8 shows that the inlet distributions to the industrial cyclones are very similar and fine, with median mass diameters around 16-17 μm and with 6-7% sub-micrometer. The much larger load at the sulphanilic acid plant produces much larger collection (99.6%) than for the biomass boiler (93.3%), as expected^{1,14,15,16}. Table II gives the most significant results obtained.

Tab. II – Results obtained in tests to cyclones, multicyclones and bag filter

	Load (g/m ³)	η (%)	Emissions (mg/Nm ³)	Emissions (kg/h)	Recirculation (%)
Cyclones RS_VHE (Sulphanilic acid)	10.98	99.58	62	0.42	13.0
	15.60	99.64	76	0.51	13.0
	7.73	99.60	42	0.25	21.3
Bag filter (Sulphanilic acid)	9.87	97.78	287	2.38	-
	15.40	98.65	270	2.25	-
Cyclones RS_VHE (Biomass boiler)	0.392	93.30	69	0.29	30.2
Multicyclones (Biomass boiler)	0.363	46.90	470	2.45	-

Fig. 9 shows that the bag-filter has grade efficiencies almost independent of particle size, as expected¹⁴, and the RS_VHE efficiencies are significantly larger than those from the multi-cyclone bank. The extremely large collection of sub-

micrometer particles is probably due to capture by larger sized particles by turbulent dispersion^{2,6,7}, much as it happened at laboratory-scale with CaCO₃.

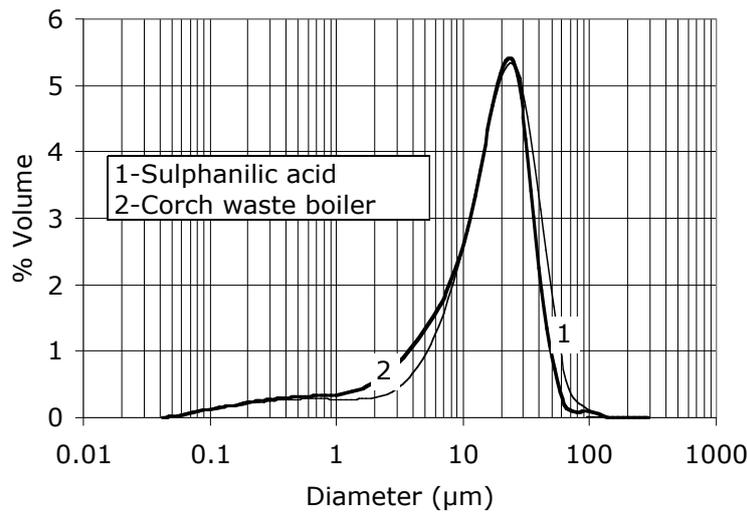


Fig. 8 – Particle size distributions at cyclone inlet

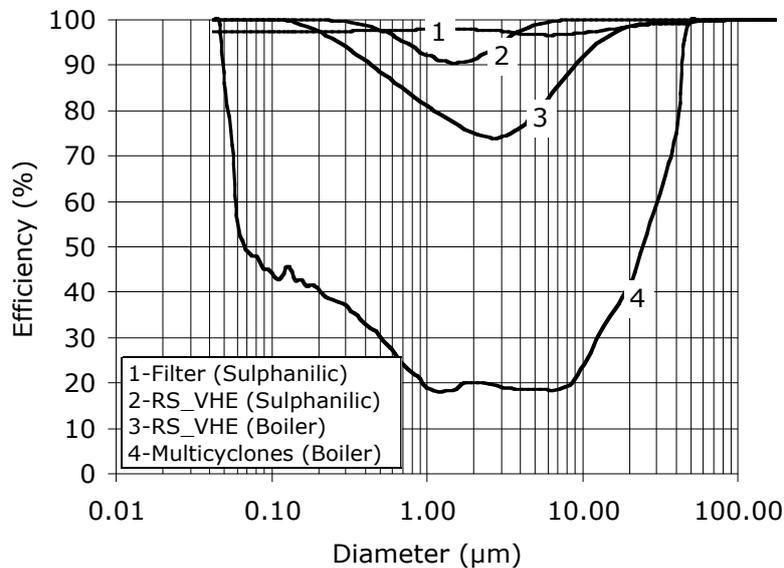


Fig.9 - Grade efficiencies at full-scale

Conclusions

The results obtained at laboratory scale of the superior behavior of the numerically optimized cyclones, relative to the Stairmand HE design, have been confirmed at pilot scale, relative to another HE design, for the recovery of fine sulphanilic acid. Typically, emissions are 50% lower. Furthermore, in the presence of partial recirculation within a collector-first arrangement, emissions drop to about 15-20% of those from HE designs and from multi-cyclone banks, both for the recovery of sulphanilic acid and fly ash from a corch waste (biomass) boiler. With high loads ($\approx 10 \text{ g/m}^3$) at the cyclone inlet, the emissions are comparable to those from on-line pulse-jet bag-filters.

The generally observed high collection of submicron particles is attributed to their capture by turbulent dispersion by larger particles within the cyclone flow field. The results so far obtained open the applicability of these simple devices to collection efficiencies typical of much more costly de-dusters, such as on-line bag-filters and venturi scrubbers.

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