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DESIGN CRITERIA OF UNIFLOW CYCLONES FOR THE SEPARATION OF SOLID PARTICLES FROM GASES

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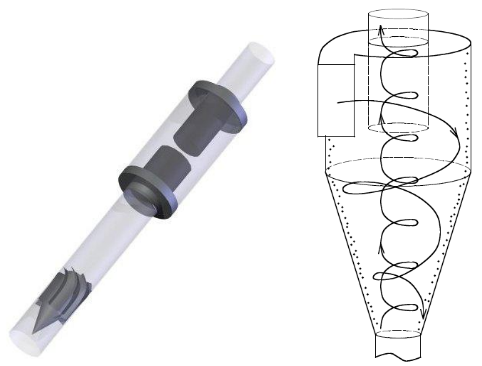
ABSTRACT

The main advantages of uniflow cyclones compared to standard reverse flow cyclones are their compact design and their capability of being easily integrated into pipelines. Experiments show that a 0.2m-diameter horizontal uniflow cyclone removes 88.6% of 2 g/m^3 of fine mineral powder (d_{10}=3μm, d_{50}=20μm) from 1000 m^3/h air at a pressure loss of 2510 Pa (0.364 psi).

INTRODUCTION

Uniflow cyclones for the separation of particles from gases have solids and gas passing through them in only one direction, Fig. 1, left. At the pipe entrance a rotational flow is generated by curved blades. Subsequently the particles are moved towards the pipe wall due to the centrifugal force. At the end of the separation chamber the particles are discharged through an opening in the wall. The clean gas leaves the separator through a central gas outlet pipe. The main difference to the standard reverse flow cyclone (Fig. 1, right) is, that in a uniflow cyclone the gas flow does not reverse.



Fig, 1. Uniflow cyclone (left) and standard reverse flow cyclone (right).

This property leads to several essential advantages of uniflow cyclones compared to standard reverse flow cyclones:

- Easy installation into pipelines
- Much smaller volume (diameter and length) needed for cleaning a given gas volume flow rate at a given pressure loss, i.e. at a given energy consumption
- Short residence time of the gas

Applications of uniflow cyclones are amongst others

- dust removal from gases on compact space
- pre-separation of particles from process gases in order to vastly increase the operation time of subsequent filters
- combustion and melting processes in metallurgy (Weng (1))
- short-contact time reaction processes (Gauthier et al. (2, 3))

Approved design criteria as well as calculation models for uniflow cyclones, which are valid for a wide range of applications, are missing up to now. Progress has been made for a few special applications:

Baluev and Troyankin (4, 5) studied uniflow cyclones for application to combustion chambers. On the basis of experiments they developed design criteria as well as calculation formulas for the tangential velocity and the pressure loss.

Gauthier et al. (2, 3) extensively investigated uniflow cyclones for separating catalyst particles from the process gas of carbon hydrogen cracking. Tests with uniflow cyclones (diameter D_C = 0.05 m) at high solids loadings (above 1wt. solids /wt. gas) and with glass beads (Sauter diameter of 29 μm) showed, that excellent collection efficiencies require short separator lengths L_C/D_C of approximately 1.5 and a proper design below the gas outlet. They showed the strong influence of air humidity on the separation efficiency.

Experiments of Zhang et al. (6) with horizontal uniflow cyclones (diameter 0.168 m) at very low crude gas particle concentrations of a few mg/m^3 showed that particles of 10 μm can be separated by an efficiency of 90%. Muschelknautz (7) derived design criteria for vertical uniflow cyclones (diameter 0.292 m) with very low pressure loss below 2 mbar for collecting coarse particles. Weng (1) developed a uniform calculation method for the pressure loss of different uniflow cyclone types (diameter 0.19 m), based on measurements of the gas flow patterns with Laser Doppler Velocimetry (LDV) and CFD simulations.

Also calculation models for uniflow cyclones have been published (Brunazzi and Paglianti (8), Tan (9, 10)). Applying these models on measurements at MCI showed good agreement with the measured overall separation efficiencies. However the calculated fractional efficiency curves deviated from the measured ones (11).

MCI intends to develop design fundamentals of uniflow cyclones for a wide range of industrial applications. Extensive studies have been performed at test facilities for vertical (diameter 0.3m) and horizontal uniflow cyclones (diameters 0.3m and 0.2m). For vertical cyclones several design parameters have been studied, such as the gas volume flow rate, the particle size distribution of the feed, the geometries of swirl vane inserts and of the vortex finder by Würtl (12), and the feed material (steel, sand, food powders, wolfram, molybdenum and others) by Leitner (13). Foidl (14) achieved a pressure recovery of 43% by installing swirl vane inserts in the gas outlet.

Open questions remaining from those investigations were: 1) how re-entrainment of particles from the dust bunker back into the clean gas can be minimized and 2) how the geometry of the swirl generator can be improved. Those problems were investigated at a test facility for horizontal uniflow cyclones (Pattis (15), Reinalter (16)).

EXPERIMENTAL SET UP

Fig. 2 shows the test facility for cyclones with an inner diameter of D_C = 192 mm.

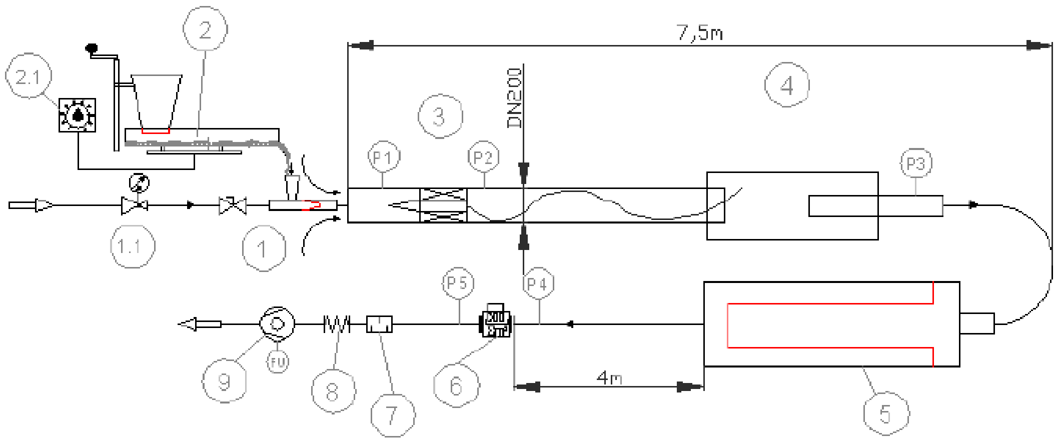


Fig. 2. Scheme of the test plant. 1. Injector (1.1 pressurized air), 2.Vibrating feeder (2.1 Potentiometer for mass flow control), 3. Swirl generator, 4. Dust bunker, 5. Filter, 6. Orifice measuring the gas flow rate, 7. Sound absorber, 8. Compensator, 9. Radial fan.

The solid particles are fed into the gas flow by a hopper, a vibrating feeder (2) and an injector (1). The gas streams first through a 2 m long inlet pipe in order to uniformly distribute the gas velocity as well as the particle concentration over the pipe cross section before entering the cyclone. To allow visual observations the inlet pipe, the cyclone body and the particle collection chamber are made from Plexiglas.

As test dusts, limestone powders with two different particle size distributions have been chosen: Carolith 20-R with d_{10} = 3 μm and d_{50} = 20 μm as well as Carolith 0-0,2 with d_{10} = 5 μm and d_{50} = 65 μm.

The collection efficiency has been determined from the mass of the collected particles $m_{Collected}$ and the mass of the feed m_{Feed}.The fractional efficiency was calculated from the particle size distributions of the feed $Q_{3,Feed}$ and of the fines $Q_{3,Fines}$. The latter has been measured in-line on probes by isokinetic sampling 4 m after the entrance of the gas outlet. At this position the former swirling flow has already been transformed into a pure axial flow by a flow straightener and the diameter has been widened onto 300 mm. Probes at 5 positions distributed over the cross section have been taken. $Q_{3,Feed}$ has been measured off-line on a probe taken from the hopper.

The cyclone pressure loss Δp has been measured as the difference of the static pressures p_1 at a position 0.2 m before the swirl generator, and p_3 at 1.4 m (i.e. 12 pipe diameters) after the entrance of the gas outlet with diameter 117 mm (Fig. 2).

All tests presented here were performed with a gas flow rate of 1000 m^3/h ($\pm 30\,m^3/h$) and a solids concentration in the crude gas of 2g/m^3 ($\pm$0.08 g/m^3). The variations during one test are shown in brackets. Every test was performed at least twice. All tests showed that, for a given set of cyclone-geometry and operation data, the measured separation efficiencies, η, deviated from the mean value by a maximum of $\pm 0.5\%$. In all tests a feed mass of 250 g was used. During all tests the air humidity was between 25 and 35%, and the temperature between 12 and 18°C.

RESULTS

Three uniflow cyclone types have been investigated:

- Type 1: Swirl vane inserts (SVI), ring slot for solids discharge (15, 16)
- Type 2A: Swirl vane inserts (SVI), window for solids discharge (16)
- Type 2B: Spiral (SP) as swirl generator, window for solids discharge (15)

Two swirl vane inserts have been tested: SVI-30° with a vane angle of 30° and SVI-50° with a vane angle of 50°, measured between the vane line at the core and normal to the cyclone axis. The vortex finder diameter D_{VF} was in all cases 117mm.

Uniflow cyclone type 1: Swirl vane inserts and ring slot for solids discharge

The swirl generator consists of 6 curved vanes arranged around a cylindrical core, the solids discharge opening is a ring slot, see Fig. 3.

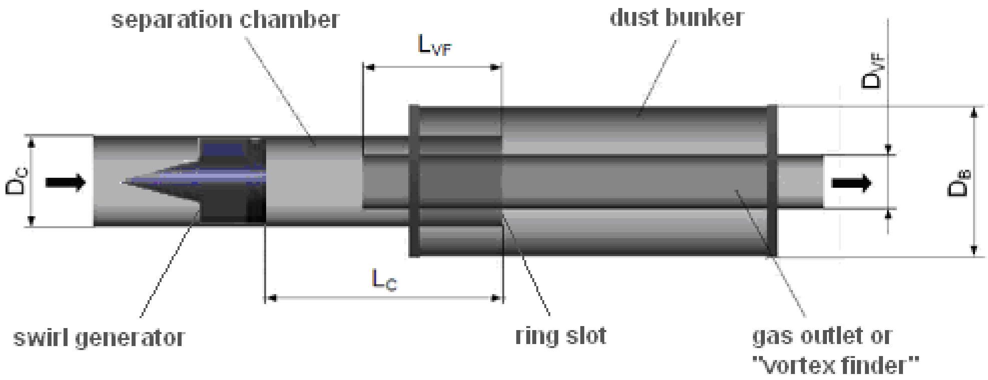


Fig. 3. Uniflow cyclone with ring-slot shaped solids discharge opening.

Maximum separation efficiencies achieved by this device were:

SVI-30°: η = 87.9% at Δp = 4125 Pa (0.598 psi) for L_C/D_C = 1, L_{VF} = 0 mm.
SVI-50°: η = 82.0% at Δp = 1860 Pa (0.270 psi) for L_C/D_C = 1, L_{VF} = 0 mm.

For optimum separation efficiencies a short s*eparator length, L_C*, between the end of the swirl generator and the beginning of the discharge opening is required, Fig. 4.

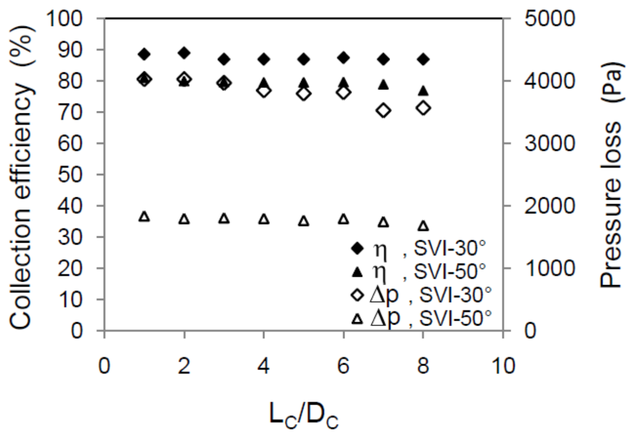


Fig. 4. Performance data of Uniflow Cyclone type 1 as a function of separator length L_C (Carolith 20-R, L_{VF}=0mm).

The *vortex finder length, L_{VF}*, crucially influences the collection efficiency. The optimum length is L_{VF}=0 mm, see Fig. 4. Sticking the vortex tube into the separation chamber up to 100 mm (positive values of L_{VF}, see Fig. 3) leads to a small decrease of η by 2%. If L_{VF}<0, then separation passes first a local minimum at L_{VF}=-200mm and breaks down for L_{VF}<-600mm. The pressure loss depends only weakly on L_{VF}.

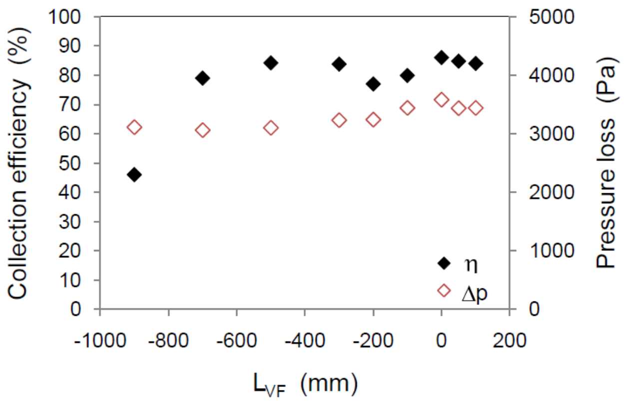


Fig. 5. Performance data of Uniflow Cyclone type 1 as a function of vortex finder length L_{VF} for swirl generator SVI-30° (Carolith 20-R, L_c/Dc = 7).

The collection efficiency depends strongly on the feed's *particle size distribution:*

		Carolith 20-R (d_{10} = 3 μm, d_{50} = 20 μm)	Carolith 0-0.2 (d_{10} = 5 μm , d_{50} = 65 μm)
η	%	86.7	94.1
Δp	Pa	3651	3420

Table 1: Separation efficiency and pressure loss for different particle size distributions of the feed (Uniflow Cyclone with SVI-30°, L_C/D_C = 7, L_{VF} = 150 mm).

Uniflow cyclone type 2: Window for solids discharge

This uniflow cyclone type has a window for the solids discharge in connection with a rectangular box as dust bunker, similar to that investigated by Zhang (6). Two variants of this cyclone type have been tested: Variant 2A with swirl vane inserts (Fig. 6, left) and variant 2B with a spiral (Fig. 6, right) as a swirl generator.

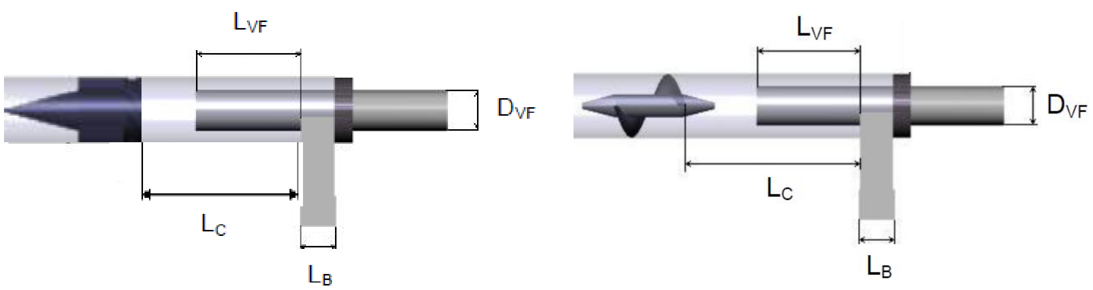


Fig. 6 Uniflow cyclone with window-shaped opening for solids discharge (L_B = length of bunker). Left: Variant 2A with swirl vane inserts (16), right: Variant 2B with spiral (15).

The spiral inlet of variant 2B, called SP-40°, is a single vane assembled as a spiral around a core, with a vane angle of 40° at the spiral core against the normal to the cyclone axis.

Maximum values for the separation efficiency of variant 2A (without core) were

- SVI-30°: η = 90.0 %, Δp = 4050 Pa (0.587 psi) for L_C/D_C=4.6, L_{VF} = 400 mm
- SVI-50°: η = 82.9 %, Δp = 1782 Pa (0.258 psi) for L_C/D_C=3.6, L_{VF} = 400 mm

Best values for the separation efficiencies of variant 2B were

- SP-40°: η = 88.6 %, Δp = 2510 Pa (0.364 psi) for L_C/D_C=3.6, L_{VF} = 400 mm

If in variant 2A (L_{VF}=400mm) a *core* is installed, which elongates the swirl vane inserts core up to the vortex finder, the separation efficiency decreases with increasing core length by up to 2%. At a core length of 1000 mm the separation efficiency for Carolith 20-R decreases to 87.5%, but also the pressure loss decreases to 3250 Pa.

The *separator length* L_C (see Fig. 6) should again not be too large. The best performances are obtained for L_C/D_C = 3 to 5, cf. Fig. 7.

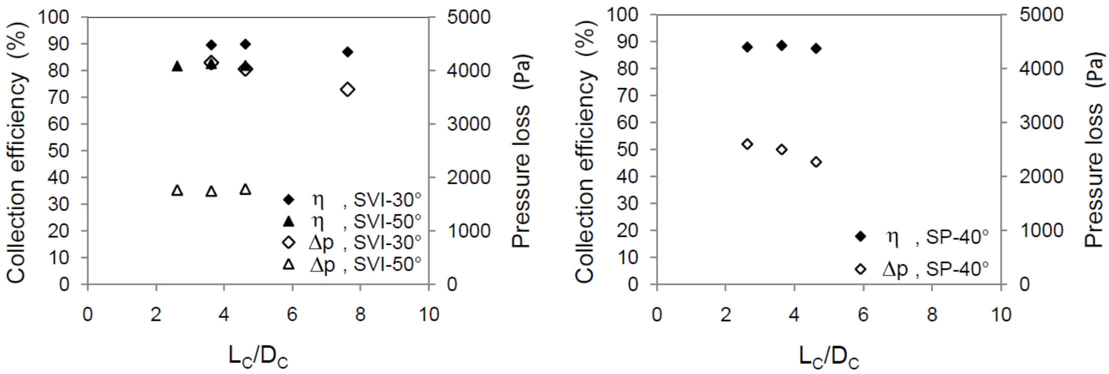


Fig. 7. Performance data of Uniflow Cyclone type 2A (left) and type 2B (right) as a function of separator length L_C for swirl generators SVI-30° and SVI-50° (both types with Carolith 20-R, L_{VF} = 400 mm, without core).

The *vortex finder length* L_{VF} (see Fig. 6) has its optimum value at 400 mm (Fig. 8).

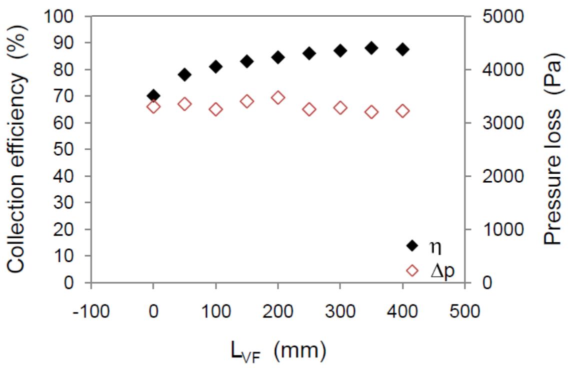


Fig. 8. Performance data of Uniflow Cyclone type 2A as a function of vortex finder length L_{VF} for swirl generator SVI-30° (Carolith 20-R, core length 1000 mm).

Influence of the *particle size distribution of feed* on the cyclone performance:

		Carolith 20-R (d_{10} = 3 μm, d_{50} = 20 μm)	Carolith 0-0.2 (d_{10} = 5 μm , d_{50} = 65 μm)
η	%	88.6	96.0
Δp	Pa	2510	2425

Table 2: Cyclone performance of Uniflow Cyclone type 2B, L_C/D_C = 3.6, L_{VF} = 400 mm.

Fig. 9 shows the fractional separation efficiency η_F of the uniflow cyclone variant 2B. The minimum of η_F may be explained as the result of particle agglomeration.

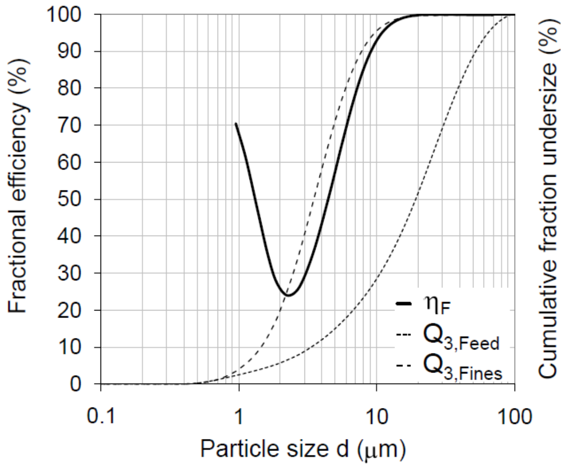


Fig. 9. Fractional separation efficiency of Uniflow Cyclone type 2B (L_c/D_c =3.6, Carolith 20-R, η = 88.6%, Δp = 2510 Pa). Dashed curves: Cumulative fractions undersize of feed and fines (Measurements by Laser Diffraction).

CONCLUSIONS

Compared to standard cyclones, uniflow cyclones are able to clean a given gas particle flow using a much more compact cyclone body. A spiral as swirl generator needs much less pressure loss than swirl vane inserts, for the same collection efficiency. Future studies will be focused on the influence of the solids loading.

ACKNOWLEDGMENT

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NOTATION

d	Particle size (μm)
d_{50}	Particle diameter for 50% cumulative fraction undersize (μm)
d_{10}	Particle diameter for 10% cumulative fraction undersize (μm)
D_C	Diameter of cyclone (mm)
D_{VF}	Diameter of vortex finder (mm)

L_C Length of separation chamber (mm)
L_{VF} Length of vortex finder (mm)
$m_{collected}$ Mass of collected particles (g)
m_{feed} Mass of feed (g)
m_{fines} Mass of fines (g)
$Q_{3,Feed}$ Cumulative volume fraction undersize of feed (%)
$Q_{3,Fines}$ Cumulative volume fraction undersize of fines (%)

Greek:

Δp Pressure loss (Pa)
η Total separation efficiency (%)
η_F Fractional separation efficiency (%)

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