PERFORMANCE COMPARISON OF UNIFLOW CYCLONES AND STANDARD CYCLONES

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Abstract – Uniflow cyclones represent a compact and competitive alternative to standard reverse flow cyclones for separating solid particles from gases. They have gas and particles passing through them in only one direction. The swirling flow inside the cyclone is usually generated either by swirl vane inserts or by a tangential inlet at the entrance of the device. Pure gas and collected particles are leaving the device at the same end. The compact design of uniflow cyclones is appropriate in space-limited applications and generally allows simple and cheap implementation into piping systems, e.g. as third stage separators in the FCC process.

Even though the principle of uniflow cyclones has been known for a long time, not much literature has been published on how to design them and to calculate their performance data. Furthermore, there seems to have been until now a lack on a systematic comparison of the performance of uniflow cyclones and standard cyclones. For calculating the performance data of conventional reverse flow cyclones, approved analytical models with high precision exist. An analogous calculation model for uniflow cyclones has been developed recently and validated by experimental data. Applying the models for standard cyclones and uniflow cyclones, which are both based on the same physical concepts, allows comparing the performance data of both cyclone types by way of calculation. For this purpose various dedusting problems have been considered specified by their operation data, i.e. gas volume flow, particle size distribution and concentration of the solids feed and a given pressure drop. For both cyclone types typical geometrical proportions have been set. The uniflow cyclones have been assumed to be oriented horizontally. It is shown that uniflow cyclones need considerable smaller diameters and lengths than their standard cyclone counterparts. Uniflow cyclone separation efficiencies approach those of standard cyclones when the particle size of the feed increases and the gas volume flow i.e. the cyclone size decreases. Thus, it can be concluded that for separating particle feeds which are not too fine or for purifying small gas volume flows a uniflow cyclone can be a more preferable option than a standard cyclone since it needs considerably less space (besides its easy integration into piping systems) and can achieve separation efficiencies very close to those of a corresponding standard cyclone. For very fine powders or for larger gas volume flows it seems to be useful to install several uniflow cyclones in parallel if a separation efficiency is required which is achievable by standard cyclones.

INTRODUCTION

A much more compact and competitive alternative to the standard cyclone, also called reverse flow cyclone ue to the reverse flows of solids and clean gas within the device, is the uniflow cyclone. Uniflow cyclones have gas and particles passing through them in only one direction. The swirling flow inside the cyclone is usually generated either by swirl vane inserts (Fig. 1) or by a tangential inlet at the entrance of the device. Pure gas and collected particles are leaving the device at the same end. The compact design of uniflow cyclones is appropriate in space-limited applications and generally allows simple and cheap implementation into piping systems (Fig. 2). Even though the principle of uniflow cyclones has been known for a long time, not much literature has been published on how to design them and to calculate their performance data. To fill this gap systematic experimental studies have been performed recently, e.g. by Weng, 2002, Würtl, 2007, Foidl, 2008, Leitner, 2008, Muschelknautz et al., 2011, Kraxner et al., 2011, Kraxner, 2013. However, up to now, not much is known how uniflow cyclones perform compared to standard cyclones. Thus, there is a need for comparing the performance of both cyclone types in a systematic way. So far the investigation of uniflow cyclones has been restricted to special applications such as uniflow cyclones with high solids loading for the application as a short-contact time reactor (Gauthier et al., 1990). A major challenge to make uniflow cyclones accessible to general industrial practice is an accurate, reliable and fast design method. For calculating the performance data of conventional reverse flow cyclones, approved analytical models with high precision exist which are often preferred over methods based on numerical simulation with long computing times.

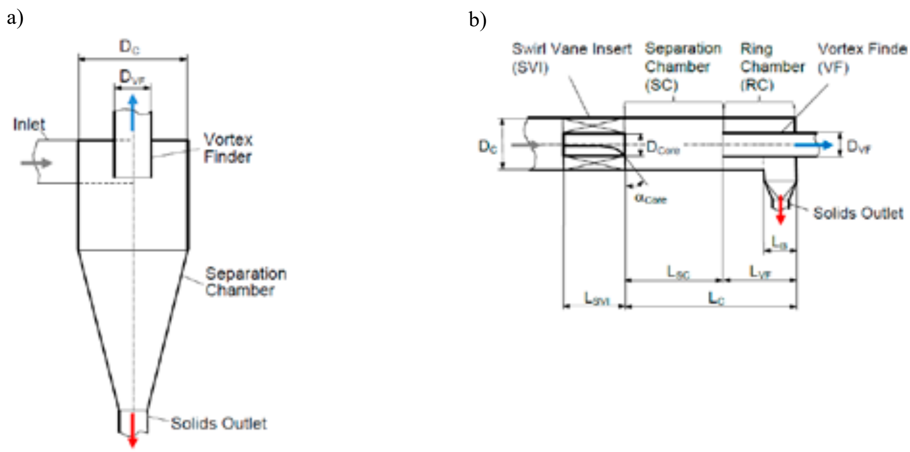


Fig. 1. Main design parameter of a standard reverse-flow cyclone (a) and a uniflow cyclone with swirl vane inserts (b). D_C: cyclone diameter, L_C: cyclone length, D_{VF}: vortex finder diameter, L_{VF}: vortex finder length, D_{Core}: core diameter, L_B: bunker length, α_{core}: guide vane angle at the core.

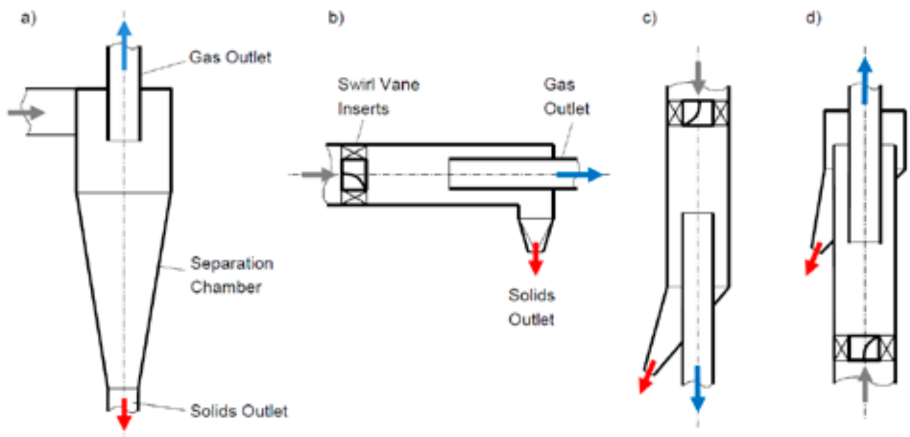


Fig. 2. Schematic illustration of a standard cyclone (a) and uniflow cyclones with axial inlet and horizontal (b), vertical downward (c) and vertical upward orientation (d).

Similarly, industrial design practice for uniflow cyclones would benefit from an adequate analytical model. An additional advantage of an analytical approach is that it requires developing a clear understanding of the underlying physical processes which simplifies generating an universally applicable model and helps to make further experimental research more goal oriented.

Former analytical approaches for calculating the uniflow cyclone separation efficiency are mostly based on the idea of a sedimentation process taking place under the effect of the centrifugal force. This conception insufficiently considers the drag force on the particles induced by the inward gas flow streaming directed towards the gas outlet pipe (Fig. 3). As this drag force has a crucial impact on the cyclone`s separation efficiency, the models incorrectly predict fundamental interrelationships like the dependency of the separation efficiency on the vortex finder diameter or on the cyclone length. Moreover, those approaches do not take into account particle re-entrainment from the ring chamber zone around the vortex finder back into the gas exit and also the influence of the solids loading on the performance data is not considered.

With this background, a new analytical approach for calculating the separation efficiency and the pressure drop of uniflow cyclones for practical design work has been developed. This approach is based on an equilibrium orbit concept similar to that applied in the Barth-Muschelknautz model for reverse flow cyclones, which has been proven to work successfully in a broad range of industrial applications. More detailed information about this model can be found e.g. in (Muschelknautz and Greif, 1997). It seems to make sense adapting the Barth-Muschelknautz model by appropriate changes for uniflow cyclones, since the principle of gas-particle separation is the same in both cyclone types, i.e. the separation results from centrifugal forces induced by a swirling flow balanced by drag forces. The novel model has been implemented into a calculation program and validated by experimental data. The publication of a detailed description of the complete model is under progress.

Applying the calculation models for standard cyclones and for uniflow cyclones which both are based on the same physical concepts a systematic comparison between both cyclone types can be performed by way of calculation. The study is in the present stage restricted to uniflow cyclones with an axial inlet and for solids loadings at the inlet up to 0.05 representing the operating range of the majority of uniflow cyclones.

CALCULATION METHOD

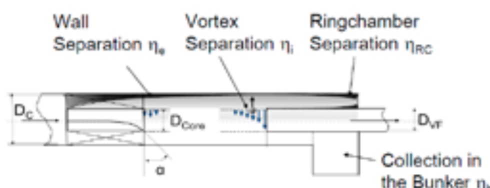
Separation efficiency

The model for standard cyclones assumes a limited loading capacity of the gas stream splitting the separation procedure in two steps. At any solids loading μ in excess of this critical loading μ_{lim}, the solids are immediately separated from the gas at the inlet to the cyclone. The solids remaining in the gas are separated in the cyclone barrel and in the inner vortex below the gas outlet tube with a second, inner separation efficiency η_i. The total separation efficiency of the cyclone is described by the equation

$$\eta = \left(1 - \mu_{\lim} / \mu\right) + \left(\mu_{\lim} / \mu\right)\eta_i \tag{1}$$

Analogous to the model for standard cyclones, it is assumed that both separation processes also occur in uniflow cyclones, Fig. 3. The first separation takes place inside the swirl vane inserts and subsequently in the separation chamber due to exceeding the limited load ratio μ_{lim} of the uniflow cyclone. If the load ratio at the inlet μ exceeds the limited load ratio, μ_{lim} , the excess mass fraction will be removed immediately after the gas jet enters the cyclone, and only a small fraction that is restricted by μ_{lim} will undergo the centrifugal separation process in the inner vortex of the cyclones.

Deviating from standard cyclones a third separation process occurs in uniflow cyclones: In contrast to standard cyclones the solids discharge in uniflow cyclones is located closely to the gas exit. Furthermore, a considerable part of the gas flow passes through the ring chamber between the cyclone wall and the vortex finder pipe before it leaves the device through the gas exit pipe. Due to those characteristics particles carried into the ring chamber can be re-entrained back into the gas outlet. The efficiency of the gas particle separation within the ring chamber is called η_{RC}. Finally, the collection efficiency of the bunker η_b has to be taken into account, as in standard cyclones. Thus, the total separation efficiency as well as the fractional separation efficiency of the cyclone are functions of those four single separation efficiencies.



$$\eta_{tot} = \eta_{tot}(\eta_e, \eta_i, \eta_{RC}, \eta_b)$$

$$\eta_{F,tot}(d) = \eta_{F,tot}(d, \eta_e, \eta_i, \eta_{RC}, \eta_b)$$

Fig. 3. Overall structure of the separation process in a uniflow cyclone.

The calculation of the *separation in the inner vortex* η_i has been described in detail in (Muschelknautz, 2012 and 2015). For low loadings μ close to 0.001 this separation mechanism is dominant and its efficiency is expected to be close to the total separation efficiency. With increasing solids loadings the wall separation becomes more and more important and already below a solids loading of 0.01 the wall separation can become the dominant separation mechanism depending mainly on the cyclone size, the tangential velocity at the inlet and on the size distribution and density of the particles.

Pressure drop

Analogous to reverse flow cyclones the pressure drop of uniflow cyclones is calculated as the difference of the total pressures between a position 0 in front of the cyclone inlet and a position m far beyond the opening of the gas outlet where the swirl strength of the vortex flow in the gas outlet has decreased to approximately zero due to wall friction, Fig. 5:

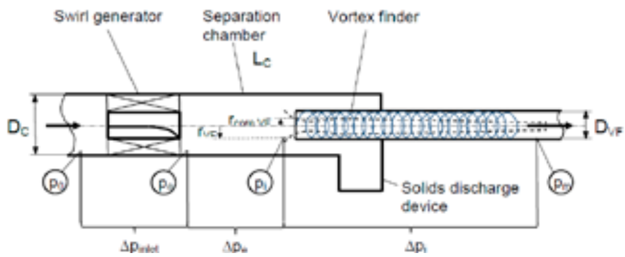


Fig. 4. Calculation of the pressure drop of uniflow cyclones.

The total pressure drop is given by

$$\Delta p\big|_0^m = p_0 - p_m = \left(p_{0,stat} + \frac{\rho}{2} \overline{v_z}^2 \right) - \left(p_{m,stat} + \frac{\rho}{2} v_i^2 \right) \tag{2}$$

Here, $p_{0,stat}$ and $p_{m,stat}$ are the static pressures at the positions 0 and m and $\overline{v_z} = \dot{V}/(\pi\, r_c^2)$ and $v_i = \dot{V}/(\pi\, r_{VF}^2)$ are the mean axial velocities in the crude gas duct and in the gas outlet duct.

As in standard reverse flow cyclones it is appropriate to divide the total pressure drop into three parts

$$\Delta p\big|_0^m = \Delta p_{inlet} + \Delta p_e + \Delta p_i \tag{3}$$

where Δp_{inlet} is the pressure drop of the inlet, Δp_e is the pressure drop in the separation chamber between the mean entrance radius r_e and the position i at the vortex finder radius r_{VF}, and Δp_i is the pressure drop between the position i and the measurement position m in the gas outlet tube, also called the vortex finder, see Fig. 4. The calculation method is based on the gas velocity field applied also for calculating the separation efficiency. Thus both calculation quantities are strongly linked within this calculation model. Furthermore, the model allows to calculate the pressure drop of a uniflow cyclone for arbitrary positions of the downstream pressure p_m in the gas exit pipe e.g. at positions only a few l/D after the gas exit pipe opening, i.e. at a point where the gas flow has still a strong vortex strength. This is especially useful for comparing calculation results with experimental data since p_m is often measured within shot distances to the gas exit pipe opening. A detailed description of the calculation method for the pressure drop can be found in (Muschelknautz, 2015).

COMPARING PERFORMANCE DATA OF BOTH CYCLONE TYPES

The model for standard cyclones and the model for uniflow cyclones described above allow to compare both cyclone types in a systematic way. With respect to industrial applicability a key question is which amount of particles both cyclone types can remove from specified gas-solids flows.

To gain an initial overview regarding this question typical uniflow cyclones and standard cyclones are designed for purifying 4 different gas volume flows between 24 m^3/h and 6640 m^3/h (air at 20°C, 1.013 bar) carrying 2 g/m^3 dust. All uniflow cyclones are geometrically similar and operate at the same static pressure drop of 4000 Pa. The same applies to the 4 standard cyclones. In this exemplary comparison all considered cyclones are installed in a pipe with the same inlet and outlet gas velocity. The pressure drop is determined as the difference of static pressures between the inlet duct and the outlet duct. If in an practical problem the inlet and the outlet gas velocity would have different values, the pressure drops calculated here would increase or decrease by the difference of the dynamic pressures which is however for both cyclone systems – uniflow cyclones and standard cyclones – the same change. All cyclone configurations have been calculated for three dusts with different particle size distributions (see. Table 1), and a particle density of 2700 kg/m^3.

Table 1. RRSB particle size distributions of the considered dusts.

Dust	d_{min}	d_{max}	$d_{50,3}$	n
Semicoarse dust	0.5	300	50.5	0.9
Fine dust	0.2	200	17.5	0.95

The design of those cyclones leads to the following results:

Uniflow cyclones for solving this problem have diameters between 30 mm (24 m^3/h) und 500 mm (6640 m^3/h) whereas standard cyclones need diameters between 54 mm (24 m^3/h) and 900 mm (6640 m^3/h), Fig. 5. The total lengths (including the length of the swirl generator) vary between 110 mm and 1830 mm for uniflow cyclones and between 150 mm and 2580 mm for standard cyclones, Fig. 5. Thus, in the present case uniflow cyclones are about 40% smaller in diameter and about 30% shorter than standard cyclones for purifying the same gas solids flows at a given pressure drop, representing typical conditions.

Note, that an increase of the length of uniflow cyclone beyond a value of $L_c/D_c \approx 3$ does not improve its separation efficiency (Muschelknautz et al., 2011). This constitutes an essential difference to standard cyclones where the separation efficiency increases with increasing separator height since the cut-off size decreases with increasing height L_i below the vortex finder according to eq. (2) as long as this height does not exceed a critical value where the inner vortex starts to bend to the cyclone wall and to suck off particles into the gas exit.

Fig. 5 shows the separation efficiencies calculated for those cyclones for semicoarse dust with a mean particle size of 50.5 µm (at the top) and for fine dust with a mean particle size of 15.5 µm (at the middle). The particle size distributions of both dusts are given in Table 1.

The results indicate that for a specified particle feed the difference between the standard cyclone and uniflow cyclone separation efficiencies decreases with decreasing gas volume flow and correspondingly with decreasing cyclone size. Furthermore, the difference between the separation efficiencies of both cyclone types becomes smaller with increasing particles size. Both effects can be traced back to the fact that the cut-off size of a uniflow cyclone in its present design according to Fig. 1 is slightly larger than that of a comparable standard cyclone.

A corresponding conclusion can be drawn regarding the particle density which follows from the model approach described above: For higher particle densities than the one specified above the gap between both separation efficiency curves (standard cyclone and uniflow cyclone) shown in Fig. 5 will decrease and vice versa.

In order to achieve a separation efficiency close to that of a standard cyclone also for larger gas volume flows a multicyclone arrangement consisting of several parallel cyclones is preferable (Muschelknautz, 2016). Fig. 5b shows the separation efficiency of an arrangement of 4 parallel uniflow cyclones, each having half the diameter of the uniflow cyclones considered in Fig. 5a. In addition there has been left some space between the cyclone cells. The comparison of Fig. 5a and Fig. 5b indicates that by this measure the separation efficiency of the uniflow cyclone is lifted up and comes very closely to the values obtained by the standard cyclone in the case of separating semicoarse dust. Furthermore the volume of the uniflow cyclone is still much more compact than that of the standard cyclone and the cyclone length has even been reduced (due to the smaller cyclone cells).

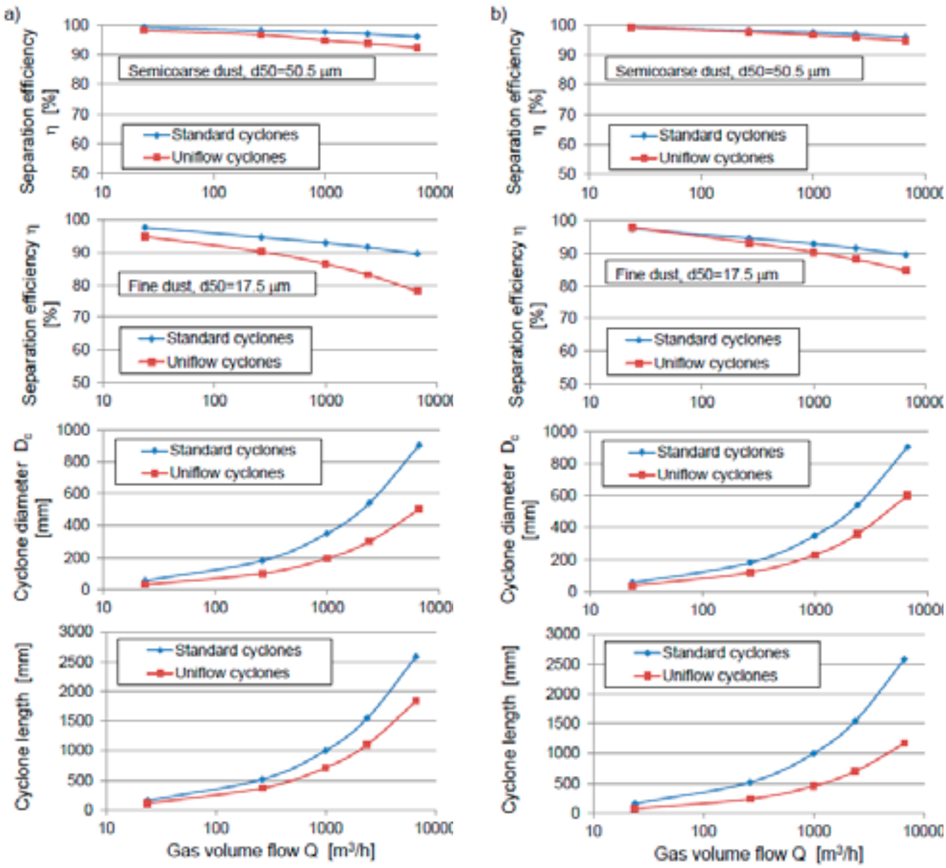


Fig. 5. Exemplary comparison of single standard cyclones with single uniflow cyclones (a) and with four parallel uniflow cyclones (b) for purifying different gas volume flows 24 m^3/h, 266 m^3/h, 1000 m^3/h, 2400 m^3/h and 6640 m^3/h. All cyclones have the same pressure drop of **ca. 4000 Pa** and are geometrically similar thus having the same inlet and outlet velocities. The main dimensions are shown in the two lower figures. Separation efficiencies are calculated for semicoarse dust with $d_{50,3} = 50.5$ µm (at the top) and for fine dust with $d_{50,3} = 17.5$ µm (at the middle) (PSD see Table 1).

Besides the separation efficiency the pressure drop is the other key parameter characterizing the performance of a cyclone. It can be reduced by geometrical modifications slowing down the gas velocities at the gas inlet and/or at the gas outlet, usually at the expense of its separation efficiency. To give an example Fig. 8 shows the separation efficiencies of standard cyclones and uniflow cyclones for the above considered gas flows between 24 m^3/h and 6640 m^3/h with diameters and lengths as specified in Fig. 6, but with reduced circumferential velocities which strongly reduce the pressure drop onto 1000 Pa. By comparing with Fig. 7 it can be seen that the pressure drop reduction distinctly affects the separation efficiencies for fine particles whereas semicoarse particles can be removed with almost the same efficiency as by the cyclones with high pressure drop. This applies to standard cyclones as well as to uniflow cyclones.

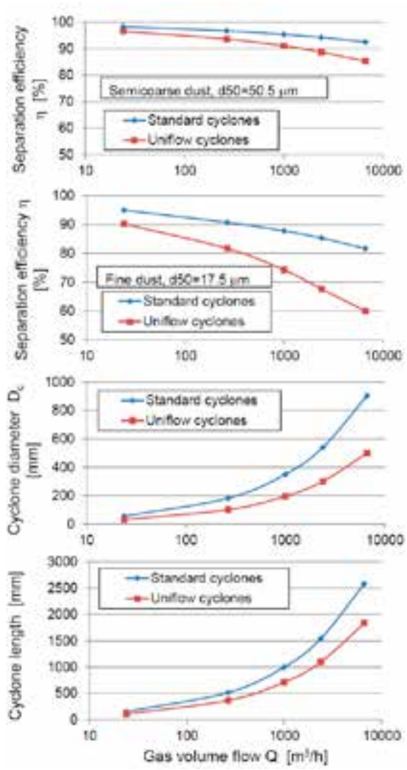


Fig. 6. Exemplary comparison of single standard cyclones with single uniflow cyclones for purifying different gas volume flows 24 m^3/h, 266 m^3/h, 1000 m^3/h, 2400 m^3/h and 6640 m^3/h. All cyclones have the same pressure drop of **ca. 1000 Pa** and are geometrically similar thus having the same inlet and outlet velocities. The main dimensions are shown in the two lower figures. Separation efficiencies are calculated for semicoarse dust with $d_{50,3}$ = 50.5 µm (at the top) and for fine dust with $d_{50,3}$ = 17.5 µm (at the middle) (PSD see Table 1).

A well proven method in industry to reduce the pressure drop of standard cyclones without affecting the separation efficiency is to install swirl vane inserts into the vortex finder to recover rotational energy (Greif, 1996, Roschek et al., 2015). Up to 60% of the total cyclone pressure drop can be regained by this measure depending on the cyclone geometry and on the operation data. Similar results can be obtained by applying swirl vane inserts in the vortex finder of uniflow cyclones (Foidl, 2008).

CONCLUSION

To compare uniflow cyclones with standard cyclones a novel calculation model for uniflow cyclones has been applied which is based on the same physical concepts as the Barth-Muschelknautz model for standard reverse flow cyclones and has been validated by experimental data. The comparison shows that uniflow cyclones in its present design are – due to their compact design and easy installation into piping lines - competitive alternatives to standard cyclone especially for small size applications. In such cases their efficiency for removing particles above 10 micron can become very close to that of corresponding standard cyclones at the same pressure consumption even if only low pressure drops of e.g. 10 mbar are allowed. For cleaning larger volume flows a multi cyclone arrangement consisting of several parallel uniflow cyclones is preferable.

NOTATION

D_c Cyclone diameter, m
D_{core} Core diameter, m
D_{VF} Vortex finder diameter, m
d_{min} Minimum particle size, m
d_{max} Maximum particle size, m
$d_{50,3}$ Mass median diameter, m
L_B Bunker length, m
Lc Cyclone length, m
L_{VF} Vortex finder length, m
L_{SVI} Length of swirl vane inserts, m
n Exponent in RRSB distribution, -
p_0 Total pressure at inlet, Pa
p_m Total pressure at oulet, Pa
$p_{0,stat}$ Static pressure at inlet, Pa
$p_{m,stat}$ Static pressure at outlet, Pa
v_i Mean axial velocity in outlet, m/s
v_z Mean axial velocity in inlet, m/s

Greek

Δp_i Pressure drop within gas outlet tube, Pa
Δp_{inlet} Pressure drop of inlet, Pa
Δp_e Pressure drop of separation chamber, Pa
$\eta_{F,tot}$ Total fractional separation efficiency, -
η_b Separation efficiency of bunker, -
η_e Separation efficiency of wall, -
η_i Separation efficiency of inner vortex, -
η_{RC} Separation efficiency of ring chamber, -
η_{tot} Total separation efficiency, -
μ Loading ratio in cyclone entrance, -
μ_{lim} Limited loading ratio, -
ρ Gas density, kg/m^3

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