Cyclone Separators for Fine Particles and Difficult Operating Conditions†

— Dedicated to Professor Gengi Jimbo on the occasion of his retirement —

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Abstract

The separation of fine particles from gases with particle sizes of about 1 μm is still a difficult problem, especially at high solids loadings of the gas stream and high gas temperatures. Practical experiences show that the separation efficiency really obtained with hot gas cleaning is generally less than calculated.

Based on new experiments and a better calculation procedure, it is also possible to use cyclone separators for these separation problems.

For a successful solution, it is necessary to increase the knowledge about the gas/solids flow and to pay attention to the boundary layer flow within the cyclone, but also to think about new multi-stage separation processes.

1. Introduction

The main design parameters of cyclones, namely pressure drop and separation efficiency, can be calculated with a number of models which have been developed on the basis of experimental data received under environmental conditions, i.e. at ambient pressures and temperatures. It has been shown by T. Lorenz [1] that based on these models, the separation efficiency of hot gas cyclones is always predicted as too good. One reason for this result is the dramatic change of the gas flow due to the increasing gas viscosity, which goes hand in hand with changes of the boundary layer flow.

Another approach to increase the separation efficiency is the use of a special multi-stage process. Similar to the separation of a solid/liquid suspension in a hydrocyclone, a certain amount of gas is removed along with the separated solids through the cyclone underflow. K. Inoya et al. [2] used such a cyclone system as a classifier for small particles and showed that a shift to the separation of smaller particles is possible.

For gas cleaning, especially hot gas cleaning, two cases have to be considered:
- Gas cleaning at low solids loadings (gas turbine process)
  In the first case, it is necessary to also remove the very fine particles, whereas in the second case, the turbine manufacturers limit the acceptable solids loading to very low values, and the tolerated maximum particle size is also rather small.

2. Separation at high solids loadings

It is well known that the separated particle sizes, mostly characterized by the cut-size diameter \(d_p\), strongly depend on the tangential gas velocity \(u_t\). Following W. Barth’s proposal [3], the largest tangential gas velocity on the radius of the gas outlet pipe can be calculated for very small solids loadings as follows:

\[
\frac{u_{tg}}{w_i} = \frac{1}{F_s \frac{\alpha}{F_i} \frac{r_o}{r_i} + \lambda} \frac{h}{r_i}
\]

\(h\) describes the equivalent friction height of the cyclone which is calculated from:

\[
h = \frac{F}{2\pi(r_o \cdot r_i)^{1/2}}
\]

\(F\) is the total cyclone surface, at which friction losses take place. (Cylinder and cone, cover plate and outer outlet duct surface.)
with:

\[ r_\alpha = r_a - \frac{b}{2} \]  \hspace{1cm} (3)

and

\[ \alpha = \left(1 - 0.54 - \frac{0.153}{F_g/F_i} \frac{b}{r_a} \right)^{1/3} \]  \hspace{1cm} (4)

For a slit gas entrance [4], the tangential velocity can be calculated. The cyclone dimensions are given in Fig. 1.

E. Muschelknautz [5] has measured the decrease of the tangential velocity as a function of the solids loading. As can be seen from Fig. 2, the related tangential velocity \( u_i/u_{i0} \) decreases remarkably and for a solids loading of about \( \mu = 2 \), the tangential velocity is only 50 % of the value obtained with a solids-free gas stream.

Calculating the cut-size diameter [6]

\[ d_p^* = \left[ \frac{18\eta w_{r1} r_i}{u_i^2 (\rho_p - \rho)} \right]^{1/2} \]  \hspace{1cm} (5)

with

\[ w_n = \frac{\dot{V}}{2\pi r_i h_i} \]  \hspace{1cm} (6)

the influence of the real tangential velocity becomes obvious.

For higher solids loadings, it has to be considered that similar to pneumatic conveying, the gas stream entering the cyclone can only carry a certain amount of solids. The solid material exceeding this maximum solids loading is separated immediately in the entrance region, and this is important, almost without any fractionation of the solids. This means that also very fine particles are thrown directly to the cyclone wall within the bulk. The maximum solids loading depends on:

\[ \mu_{\text{max}} = \left( \frac{u_i}{w_i} \right)^{3/2} \left( \frac{w_s^*}{w_{s50}} \right) \]  \hspace{1cm} (7)

with \( w_s^* \) as the settling velocity of particles with the cut-size diameter \( d_p^* \) of the cyclone, and \( w_{s50} \)
as the settling velocity of particles corresponding to the 50 % value of the particle size distribution entering the cyclone.

Details on the calculation of the maximum solids loading have been published by E. Muschelknautz [7], M. Trefz [8] and W. Rentschler [9].

3. Multi-stage separation process

To increase the separation efficiency of cyclones, a technique used with hydrocyclones may be advantageous. First experiments in this field have been carried out by K. Inoye et al. [2]. Their experimental set-up is shown in Fig. 3. Their intention was to increase the performance of a cyclone to be used as classifier. The solid particles leaving the cyclone through the underflow are separated from the gas by means of a filter. The dimensions of the cyclones used are given in Fig. 4. As can be seen from Fig. 5, the grade efficiency curve depends strongly on the amount of the blow-down gas stream. The amount is given as a percentage of the entrance flow rate. With increasing blow-down gas stream, the cut-size diameter is shifted to smaller particle sizes, and the grade efficiency curves become steeper.

To answer the question of whether a two-stage separation process with two cyclones is able to increase the total efficiency, an experimental set-up as shown in Fig. 6 was used in Braunschweig. The solids-laden blow-down gas stream of the first cyclone enters a second cyclone. The measured and calculated grade efficiency curves of both cyclones are shown in Figs. 7 and 8. The raw gas particle size distribution used for the experiments is given in Fig. 9. Table 1 shows a summary of the results, obtained with the data given in Figs. 7, 8 and 9.

Using only one cyclone, the total separation efficiency is 96.74%. Feeding the separated solids of the first cyclone with a blow-down gas stream of 10% of the entrance gas stream to the second cyclone leads to a separation efficiency of 99.81% for the second cyclone. Combining the two clean gas streams results in a total separation efficiency of the two-stage process of 98.12%. That means an increase of the total

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**Fig. 3** Experimental set-up used by K. Inoye et al. [2]

**Fig. 4** Cyclone used as a classifier [2]

**Fig. 5** Grade efficiency curves obtained for different blow-down gas streams [2]. Inlet gas velocity 25 m/s
Table 1 Comparison of a single and a two-stage separation process

|                              | single-stage | two-stage separation process |
|------------------------------|--------------|-----------------------------|
|                              | cyclone 1    | cyclone 1 and 2              |
| blow-down gas stream  $V_{bd}$ | $V_{e}$      | $V_{e}$                     |
| entrance gas flow rate  $V_{e}$ | m$^3$/h     | 180                         |
| entrance gas velocity  $w_e$ | m/s          | 13.6                        |
| raw gas solids content  $M_{Re}$ | kg/h        | 18 - 10$^{-3}$              |
| raw gas solids loading  $\rho_e$ | --          | 8.4 - 10$^{-5}$             |
| clean gas solids content  $M_{C}$ | kg/h        | 5.86 - 10$^{-4}$            |
| total separation efficiency  $\eta$ | --          | 0.9674                      |

Fig. 6 Two-stage separation process

Fig. 7 Measured and calculated grade efficiency curves of cyclone 1 for different gas streams

Fig. 8 Measured and calculated grade efficiency curves of cyclone 2 for different gas streams

Fig. 9 Particle size distribution of the solids used in the experiments
separation efficiency of 1.38%. But more obvious is the fact that the solids content in the clean gas for the two-stage process is reduced to 57% compared with the single-stage process.

4. Hot gas cleaning

It is well known from experience that cyclone separators designed on the basis of data and models obtained under ambient conditions perform much worse than calculated. To receive more reliable data, the experimental set-up shown in Fig. 10 was installed at the Institute of Chemical Engineering in Braunschweig. Measurements were carried out up to gas temperatures of 1173 K. The particle size distribution and the particle concentration in the inlet and outlet gas streams of the cyclone are measured with light scattering aerosol counters. The measured quantities are scanned and transmitted to a PC. The dimensions of the used cyclone are given in Fig. 11.

The pressure drop of the cyclone was measured as the difference between the static pressures in the inlet and the outlet duct behind a straightener for reducing the torque flow of the gas. The experimental data obtained in the temperature range between 293 and 973 K are given in Fig. 12 as pressure drop coefficients, which are calculated from:

$$\Delta p = \xi_i \frac{\rho}{2} w_i^2$$ (8)

For the precalculation of the pressure drop coefficient, it is useful to separate it into two parts:

$$\xi_i = \xi_w + \xi_d$$ (9)

$$\xi_w$$ describes the pressure drop in the entrance region and the friction within the cyclone

$$\xi_d$$ describes the pressure drop in the outlet duct.

It is:

$$\xi_w = \frac{r_i}{r_8} \left[ \frac{1}{\left(1 - \frac{u_i}{w_i} \frac{h}{r_i} \lambda \right)^2} - 1 \right] \left(\frac{u_i}{w_i}\right)^2$$ (10)

$$\xi_d = 0.8 \left[ 3 \left(\frac{u_i}{w_i}\right)^{4/3} + \left(\frac{u_i}{w_i}\right)^2 + 2 \right]$$ (11)

The wall friction factor $\lambda$ has been measured by T. Lorenz [1]:

$$\lambda = 0.0049 + \frac{0.87}{Re_i}$$ (12)

with

\[\begin{array}{c}
\Delta p = \xi_i \frac{\rho}{2} w_i^2 \\
\xi_i = \xi_w + \xi_d \\
\xi_w = \frac{r_i}{r_8} \left[ \frac{1}{\left(1 - \frac{u_i}{w_i} \frac{h}{r_i} \lambda \right)^2} - 1 \right] \left(\frac{u_i}{w_i}\right)^2 \\
\xi_d = 0.8 \left[ 3 \left(\frac{u_i}{w_i}\right)^{4/3} + \left(\frac{u_i}{w_i}\right)^2 + 2 \right] \\
\lambda = 0.0049 + \frac{0.87}{Re_i}
\end{array}\]
The calculated pressure drop coefficient

\[ \xi_i = \frac{\Delta P}{\frac{\rho}{2} w_i^2} \]  

is plotted against Reynolds number

\[ Re = \frac{w_i d_i \rho}{\eta} \]

in Fig. 12 and shows a strong influence of the Reynolds number. The calculated curve and the measured data are in sufficient agreement.

Experimental results for the grade efficiency of the cyclone are given in Fig. 13. Using the proposal of H. Mothes et al. [10] for the calculation of the grade efficiency developed for ambient conditions, it can be seen that the calculated curves show a much better separation than actually obtained. With higher gas temperatures, the shape of the curves also changes: they become steeper. This is in agreement with theoretical considerations, but is not described correctly by the model of H. Mothes.

To improve the calculation procedure, the boundary layer flow at the cover plate and at the outer side of the outlet pipe, the reentrainment of already separated particles from the solids outlet region, and the influence of the turbulence all have to be considered. A very simplified illustration of the calculation is shown in Fig. 14. The cyclone is divided into 5 regions:

Region 1: Boundary layer flow at the cover plate and the outer side of the outlet pipe.
Region 2: Entrance
Region 3: Downstream flow
Region 4: Reentrainment
Region 5: Upstream flow

Depending on the axial coordinate \( z \), the solids concentration changes due to the separation process. The mass balance of the solids is calculated in each area of the cyclone over the height of \( dz \) as illustrated for region 3. At the height \( z \), a certain amount of particles with the same particle size enters the balance area. Some of the solids are thrown to the cyclone wall and are separated. Another part enters due to turbulence into region 5, but also particles from region 5 return to region 3. The difference between these particles leaves the balance area at \( z + dz \). This calculation has to be repeated for all particle sizes and all cyclone heights. A particles
The details of the calculation can be found in the Ph.D.-thesis of T. Lorenz [11]. The new approach gives much better results. Fig. 15 contains some of the results. The agreement between measured and calculated data is very good. For the two-stage separation process, a region 6 has to be incorporated into the model, in order to also capture the influence of the blow-down gas stream.

**Fig. 13** Measured and calculated (Mothes) grade efficiency curves

**Fig. 14** Cyclone geometry for calculation of grade efficiency

which reach the entrance of the outlet pipe are not separated within the cyclone. Comparing the amount of solids of a certain particle size in the clean gas with the amount entering the cyclone gives one point of the grade efficiency curve.

**Fig. 15** Measured and calculated (Lorenz) grade efficiency curves

**Nomenclature**

- \(a\) [m] entrance height
- \(b\) [m] entrance width
- \(d_p\) [m] particle diameter
- \(d_p^*\) [m] cut-size diameter
- \(d_{50}\) [m] 50% value of the particle size distribution
- \(F\) [m] inner cyclone surface
- \(F_{a,i}\) [m²] inlet, outlet area \(F_i = a \cdot b, F_r = \pi r_i^2\)
- \(h\) [m] cyclone friction height
- \(h_i\) [m] cyclone height below the outlet pipe
- \(\Delta p\) [Pa] pressure drop
- \(\tau_i\) [m] outlet radius
- \(\tau_s\) [m] cyclone radius
- \(Re\) [—] Reynolds number
- \(u_t\) [m/s] tangential velocity
- \(w_i\) [m/s] axial outlet velocity
- \(w_r\) [m/s] radial velocity on outlet radius
- \(w_s\) [m/s] settling velocity of particle with cut-size diameter
- \(w_{s50}\) [m/s] settling velocity of particle with a diameter corresponding to the 50% value of the particle size distribution
- \(\dot{V}\) [m³/s] gas flow rate
- \(\lambda\) [—] wall friction factor
- \(\eta\) [kg/m·s] dynamic viscosity
- \(\eta\) [—] grade efficiency
\( \rho_g \) [kg/m³] gas density
\( \rho_p \) [kg/m³] particle density
\( \mu \) [-] solids loading
\( \xi \) [-] pressure drop coefficient

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