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Determining the best modelling assumptions for cyclones and swirl tubes by CFD and LDA

Abstract

Experimental data determined by Laser Doppler Anemometry (LDA), are presented and compared with computational fluid dynamics simulations (CFD for two types of reverse-flow centrifugal separators
a) a conventional cylinder-on-cone cyclone with tangential inlet, and
b) a swirl tube with vane generated swirl and a cylindrical body
These data are used to test the validity of the flow assumptions of some widely used cyclone separation models. Emphasis has been given to the flowpattern in cylindrical swirl tubes, which have been little researched until now. Although the results globally support the common flow assumptions, we found some noteworthy discrepancies. The locus of zero axial velocity, which is often held to determine the cyclone cut size and to be a function of the diameter of the gas outlet, is shown to be largely determined by the cyclone body diameter. While the work confirms that the radial velocity is axially constant in cylinder-on-cone cyclones, it is shown not to be so in cylindrical swirl tubes, suggesting that different efficiency models may be appropriate for the two types of devices.

Introduction

Centrifugal separators, such as conventional cylinder-on-cone cyclones and cylindrical swirl tubes with swirl vanes, play a dominating role in industrial dedusting and demisting. Efficient, reliable separation is needed to meet ever more stringent environmental requirements. If at all possible, meeting new emission limits using improved cyclone technology is preferable to using more expensive and cumbersome dedusting alternatives.

Since the emergence of signal analysis also for high velocities, LDA has proven a useful tool to study the flowpattern without inserting probes, which may disturb the swirl. New data are therefore emerging regarding the flowpattern in reverse-flow dedusters, but many questions remain unanswered. In particular about the appropriateness of the sweeping flow assumptions made in most cyclone performance models.

The present paper sheds light on these issues, for cylinder-on-cone cyclones with tangential inlets, but also notably for cylindrical swirl tubes with swirl vanes. The latter device is often used in parallel in so-called swirl decks, for instance for dedusting after the FCC process. In spite of their wide use, neither dedicated performance models for swirl tubes, nor detailed information about the flow pointing to the best model assumptions, has been published.

A number of predictive models for the separation efficiency of cyclones have been proposed in the literature. The most popular modelling approach (Barth ,1956; Dietz, 1968; Mothes and Löffler, 1988) is based on a force balance on a particle swirling on the interface between the "inner" and "outer" vortex having upward and downward axial flow, respectively. Inward drag is proportional to the particle diameter (in Stokes' region), while outward "centrifugal force" is proportional to the cube of the diameter. Large particles are therefore separated, while small particles are dragged into the inner vortex and lost. These models assume axially constant tangential and radial velocities in the surface separating the inner and outer vortices, assumed to be the cylindrical surface obtained when prolonging the vortex finder (gas exit) wall to the bottom of the cyclone or swirl tube.

CFD has gained enormously in popularity as a technique for predicting the flow field and the separation efficiency. The separation efficiency is mostly predicted by Lagrangian particle tracking in a pre-calculated flow field. CFD can be very helpful for detailed investigation of the gas-solid flowpattern inside the separator body,

Experimental procedure

- Test rig

The technique of LDA was used to measure the mean fluid velocities in one cyclone and one swirl tube. The rig was situated at the Shell Research and Technology Centre in Amsterdam (SRTCA). A schematic picture of the rig is shown in Figure 1. Diagrams of the cyclone and swirl tube used are shown in Figure 2.

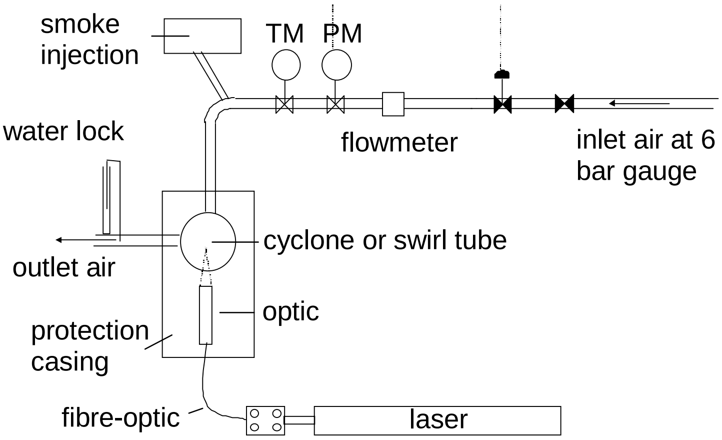

Figure 1. Experimental set up

The main advantage of LDA is that it is non-intrusive. Problems can be caused by the seed particles not faithfully following the strongly swirling gas flow, and by breaking of the laser beams in the cylindrical wall of the cyclone or swirl tube.

- Test program

Only the tangential and the axial velocity components were measured. The measurement stations are indicated in Figure 2. In the tangential inlet cyclone, LDA measurements were performed at 9 different axial stations each at 20 points in the radial direction. In the cyclone, the axial position of the stations are given as distance below the cyclone roof, divided by the total length of the cyclone, roof to dust exit: $|z|/L$. The stations were: four in the gas inlet area, the results at these stations are given in another paper, one in the cylindrical part, near the junction between the cylinder and the cone and four in the conical part.

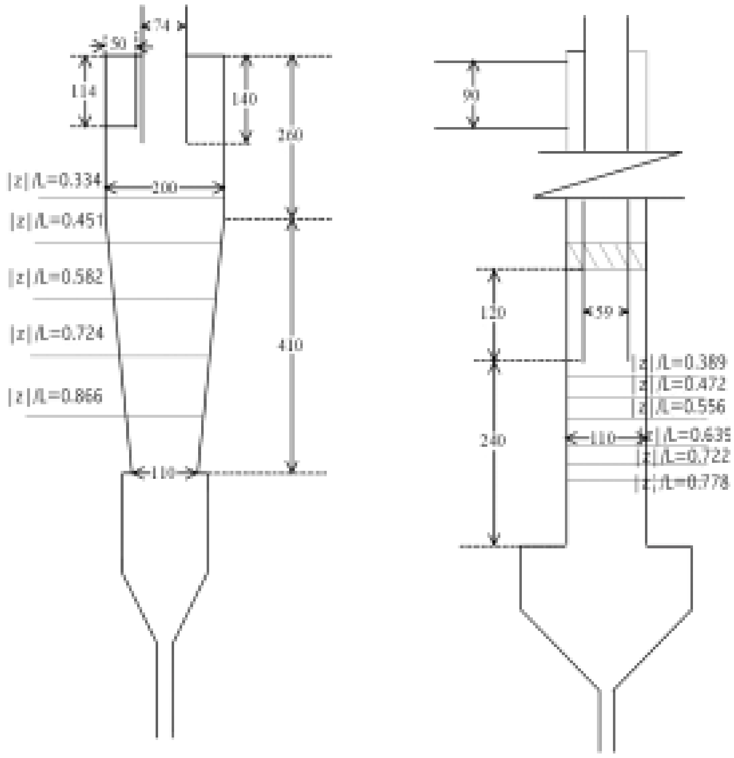

Figure 2. The construction of the cyclone (left) and the swirl tube with the axial measuring stations indicated

In the swirl tube, measurements were performed at 10 axial stations, each at 20 points in the radial direction. The axial position of the stations are given as distance below the vane pack divided by the total swirl tube length, vane pack to dust exit: $|z|/L$. There are four between the vanes and the entrance of vortex finder, which are not discussed here, one just beneath the entrance of vortex finder and five between the vortex finder and the dust outlet.

The air flow into the conventional cyclone was 200 Nm^3/h, corresponding to an inlet velocity of about 10 m/s at inlet conditions of 1.04 bar and 20.4°C. The air flow in the swirl tube was 175 Nm^3/hr, here 3% gas under flow was used, the exit angle from the vanes with the horizontal is 30^o.

- *CFD*

The CFD package used is 2-D axisymmetric using skew upwind differencing (SUDS). The turbulence model is a hybrid between an algebraic stress model and a full Reynolds stress model (Boysan *et al.*, 1986).

Results

- *Tangential velocity*

Figures 3 and 4 show the tangential velocity profiles at the stations below the mouth of the vortex finder in the cyclone and the swirl tube, respectively. As we move down the conical section of the cyclone, the position of the wall moves inward. In the cyclone, the well-known characteristic shape of the profile can be recognised, with a near loss-free profile surrounding a core of near solid body rotation. Measurements very close to the axis were impossible in the swirl tube, since no tracer particles were present there.

- *Axial velocity*

Figure 5 and 6 show the axial velocity profiles in the cylinder-on-cone cyclone and the swirl tube, respectively. Also here the characteristic shapes of the profiles can be recognised. In the cyclone, a dip in axial velocity near the axis is clearly visible. The shape of the curves is similar between the two devices and for both devices the shape more or less independent of the axial position. In the cyclone the locus of zero axial velocity seems to move inward as we move down the cone.

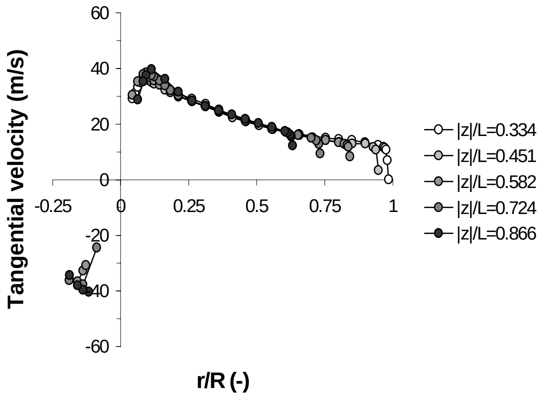

Figure 3 The tangential gas velocity in the cylinder-on-cone cyclone.

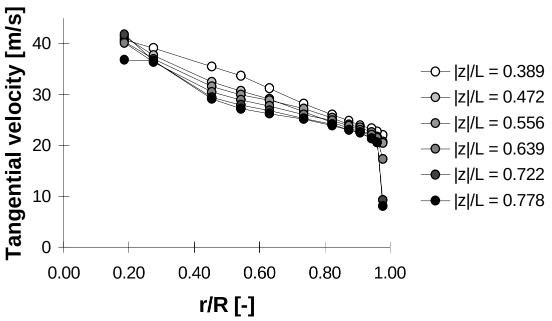

Figure 4 The tangential gas velocity in the cylindrical swirl tube.

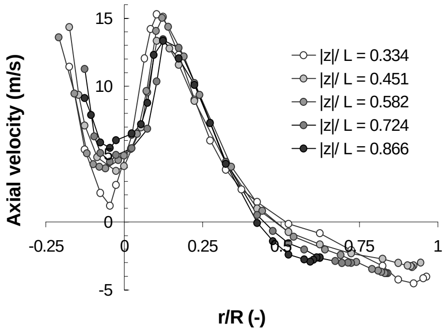

Figure 5 The axial gas velocity in the cylinder-on-cone cyclone.

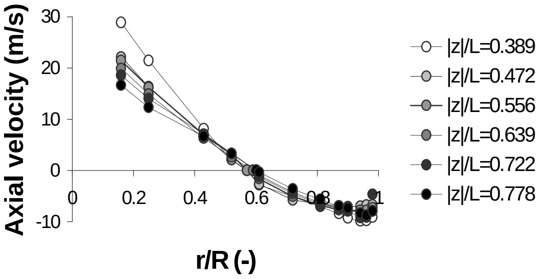

Figure 6 The axial gas velocity in the cylindrical swirl tube

- Radial velocity

The radial velocity is smallest of the three components, and could not be measured directly. However, the local radial flow across the locus of zero axial velocity from the outer to the inner vortex was calculated by finding the axial downflow at each station numerically integrating the negative part of the curves in Figures 5 and 6, and computing the differences.

The flow difference between two successive stations gives the average radial flow from the outer to the inner vortex between the two stations. If we assume that the locus of zero radial velocity is the surface *CS* (which is not exactly true), we get:

$$Q_i - Q_{i+1} = 2\pi R_{CS} \cdot \left|z_{i+1} - z_i\right| \cdot v_r = \int_{R_{CS}}^{R} 2\pi r v_z(r)\,dr \qquad (1)$$

Where, Q_i, Q_{i+1} are the total flow downward at the i^{th} and $(i+1)^{th}$ axial flow stations in the outer vortex, respectively, z_i and z_{i+1} their axial height, and v_z and v_r the axial and the radial velocity, respectively. R_{CS} is the radius of the *CS*, and *R* the radius of the wall of the separator.

The results of these calculations are shown in Figures 7 and 8.

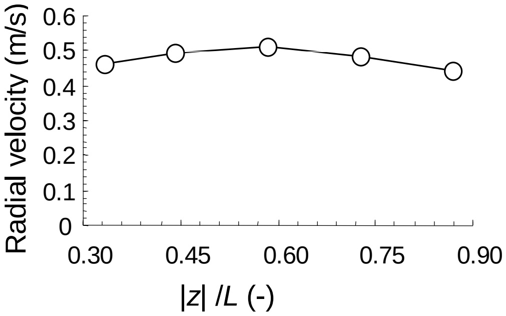

Figure 7. Axial distribution of the radial velocity in the cyclone

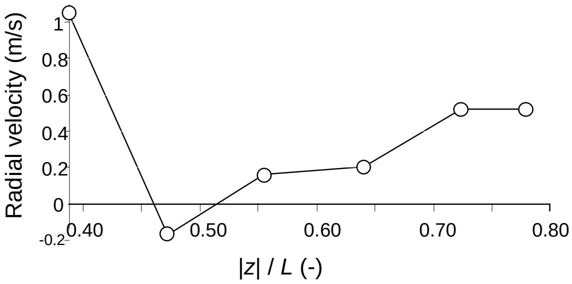

Figure 8 Axial distribution of the radial velocity in the swirl tube

Discussion

- Comparison of flowpatterns in the tangential cylinder-on-cone cyclone and the swirl tube

While the tangential velocity remains closely the same in the axial direction in the cylinder-on-cone cyclone, it tends to decrease with depth in the swirl tube. In both types of apparatus, we have to do with attenuation of swirl as we move down, further from the inlet.

One important difference between cyclone and swirl tube is in the axial distribution of the inward radial flow. Figure 7 shows that the radial velocity is almost uniform along *CS* in the cylinder-on-cone cyclone. The values are very close to the mean value of 0.46 m/s calculated from: $Q/(2\pi R_{CS}H_{CS})$, which lends credence to this indirect method of calculating the radial velocity. In the swirl tube, on the other hand, (Figure 8) there are regions of strong inward velocity just under the mouth of the vortex finder and in the bottom. Over the rest of *CS*, the inward velocity is very low. The mean value should be 1.1 m/s, higher than the mean of the values in Figure 8. The reason is probably that the two regions of high inward velocity are not covered completely by the measurements.

Computational fluid dynamics (CFD) can help in elucidating the difference in radial velocity distribution between the two devices. Figure 9 shows profile plots of the radial velocity distribution in both devices from CFD simulations.

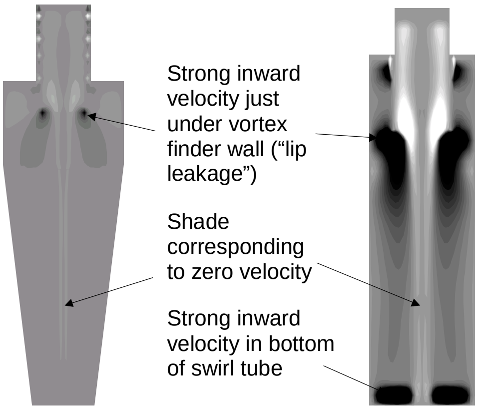

Figure 9. Profile plots from CFD simulations of the radial velocity distribution in the cylinder-on-cone cyclone and the cylindrical swirl tube

The CFD simulations show a strong inward radial flow just under the vortex finder wall in both devices; this flow is often referred to as 'lip leakage' in cyclones. A region of strong inward flow can also be seen at the bottom of the swirl tube, but not in the cylinder-on-cone cyclone. Both measurements and simulations thus indicate that the radial flow is more evenly distributed in a cylinder-on-cone configuration than in a cylindrical one.

Although the lip leakage appears more localised in the cyclone than in the swirl tube in Figure 9, it is in fact stronger: the CFD simulations show a maximum radial velocity in the cyclone 4.41 times greater than the mean axial body velocity, while the same ratio is only 1.69 in the swirl tube. It is impossible to say *a priori* what the effect of the lip leakage will be on the efficiency. Trefz (1992) studied the boundary layer flow in the inlet region of the cyclone. He found that powder flowing to the outer wall there was transported in a boundary layer flow along the roof and along the outer wall of the vortex finder to the mouth of the vortex finder, and lost in the lip leakage. The loss should thus largely be determined by the volumetric flow in the lip leakage.

- The model assumptions in the light of CFD and experiment

We now consider whether the assumptions made about the flow in cyclone performance models are reasonable in light of the measurements and numerical simulations.

One assumption is that the locus of zero axial velocity, separating the regions of downward and upward flow, coincides with the surface *CS* formed by prolonging the vortex finder wall to the bottom of the cyclone.

Figure 10 shows results of both LDA measurements and CFD in a swirl tube for two different vortex finder diameters and by CFD in a cylinder-on-cone cyclone. In 10 a) the boundary between the up- and downwardly directed flow have been pinpointed with LDA. In 10 b) and c) the loci of zero axial velocity have been made visible in a CFD flow field by plotting contour plots of $\ln(1+v_z^2)$, which shows up the locus as a black region (low contour value).

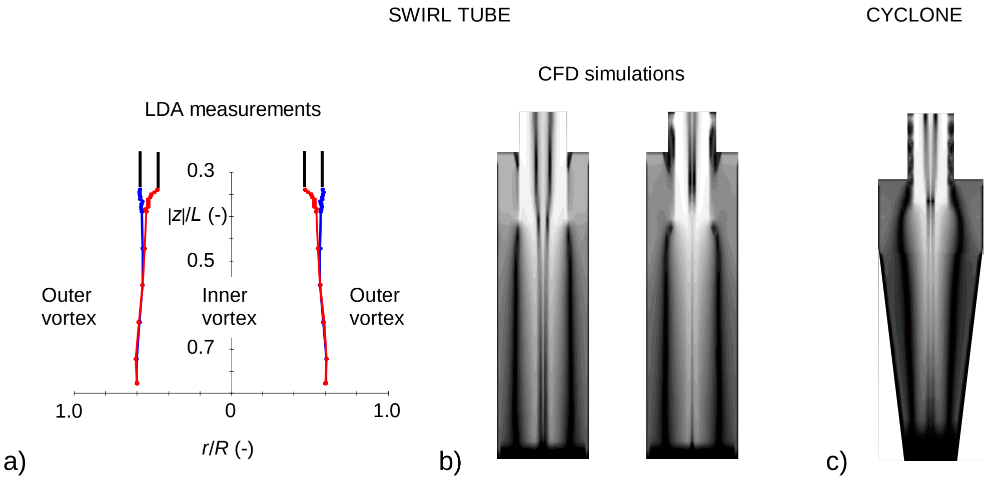

Figure 10. The boundary between upward and downward flow in the body a) in swirl tube by LDA, b) in swirl tube by CFD, c) in cyclone by CFD.

The qualitative picture for the swirl tubes is the same with LDA and CFD: for the larger vortex finder (D_x a little larger than ½D), the surface appears to be cylindrical in agreement with the model assumption, but for the smaller vortex finder, it widens under the vortex finder wall, and becomes the same diameter in the main part of the body as with the larger vortex finder. The agreement between LDA and CFD is excellent in predicting the surface of zero axial velocity.

Although the general picture therefore is in agreement with the model assumptions, the results in Figure 10 indicate that the diameter of the inner vortex is determined by D rather than D_x, except right under the vortex finder wall. This agrees with the Patterson and Munz (1996) who found little change in the locus of zero axial velocity when D_x was changed substantially.

Although we thus see that the locus of zero axial velocity is not mainly determined by the diameter of the gas outlet, the particles must still enter the gas outlet to be lost, and this is where we should seek the strong effect of the gas outlet diameter on the separation efficiency of cyclones and swirl tubes; an effect which is correctly predicted by the separation models we are considering in this paper.

We do not have direct LDA measurements of the locus of zero axial velocity in the cylinder-on-cone cyclone. Figure 10 c), shows the locus on basis of a CFD flow field. The CFD simulations confirm that the locus converges as we move down the conical section in the cyclone.

Another assumption made in models is that the swirl velocity in the cyclone is constant axially. Figure 3 shows that the tangential velocity is effectively constant at all axial positions in the cylinder-on-cone cyclone, even till deep in the conical section. In the swirl tube the tangential velocity decreases slightly as we move down. Overall, the measurements confirm the validity of this model assumption, at least for somewhat normal geometries.

A third assumption in the equilibrium orbit models is that the radial velocity is uniform over *CS*. The radial velocity is the smallest velocity component, and it is difficult to measure with LDA. Figures 7 and 8 show that the radial velocity in the cylinder-on-cone cyclone is effectively constant over *CS* except for the lip-leakage. In the cylindrical swirl tube we have two regions of strong inward flow under the vortex finder and in the bottom of the tube, while through the rest of the separation space the radial velocity is very low.

Thus, the flow assumptions made in the cyclone separation models are largely confirmed for the cylinder-on-cone geometry. For a swirl tube, however, they are less consistent with the real flow.

This difference between the two types of configuration indicates that the approach for modelling of separation performance for cylindrical swirl tubes perhaps should be different to that for cylinder-on-cone cyclones. Further work will be undertaken to formulate a reliable model for the separation efficiency of cylindrical swirl tubes.

Concluding remarks

Although the results globally support the common flow assumptions, we have found some noteworthy discrepancies. The locus of zero axial velocity, which is often held to determine the cyclone cut size and to be a function of the diameter of the gas outlet, is largely determined by the cyclone body diameter. While the radial velocity is axially constant in cylinder-on-cone cyclones, it is not so in cylindrical swirl tubes, suggesting that different efficiency models may be appropriate for the two types of devices.

Based on the results, we can draw the following conclusions:

1. The tangential velocity is axially constant in the cylinder-on-cone cyclone. In the swirl tube the tangential velocity decreases slightly as we move down.
2. The radial velocity is fairly uniform over the length of the separation zone in the cylinder-on-cone cyclone except for a strong, but localised lip-leakage. In the cylindrical swirl tube the inward flow is largely limited to regions of strong inward velocity under the vortex finder and in the bottom of the body. LDA and CFD agreed very well.
3. The flow assumptions of the successful “equilibrium orbit” models were shown to be reasonably realistic in the cylinder-on-cone cyclone, while the flow pattern - particularly the radial velocity from the outer to the inner vortex - was somewhat different in the swirl tube.

Acknowledgement

The authors would like to thank A. Berrino for expertly carrying out the CFD simulations.

Symbols used

CS	control surface
D	diameter (no subscr: of body)
H	height
L	total deduster length
r	radial coordinate
Q	volumetric flowrate
R	radius (no subscr: of body)
v	velocity
z	axial coordinate

subscripts:

CS	in the surface CS
i	index denoting the flow station
r	radial direction
x	of the gas outlet or vortex finder
z	axial direction

References:

Barth, W. “Berechnung und Auslegung von Zyklonabscheidern auf Grund neuerer Unterscuhungen”, *Brennstoff-Wärme-Kraft* , **8**, Heft 1 (1956): 1-9.

Boysan, F, Swithenbank, J. and Ayers, W.H., “Mathematical Modelling of Gas-Particle Flows in Cyclone Separators”, *Encyclopedia of Fluid Mechanics* 4 Cheremisinof (Ed.) Gulf Publ. Co., Book Division, Houston 1986: 1307-1329.

Dietz, P.W., “Collection Efficiency of Cyclone Separators”, *AIChE Journal,* **27**, No 6 (1981): 888-892.

Mothes, H. and Löffler, F., “Prediction of particle removal in cyclone separators”, *International Chemical Engineering*, **28**, No. 2 (1988): 231-240

Trefz, M., “Die vershiedenen Abscheidevorgange im hoher un hoch beladenen Gaszyklon unter besonderer Berucksichtigung der Sekundarstromung”, *Forschritt-Berichte VDI* **295** VDI-Verlag GmbH, Dusseldorf (1992).