

THE USE OF SWIRL TUBES FOR DEDUSTING.

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The use of swirl tubes in industry and the patent and scientific literature is reviewed and discussed. Swirl tubes are here defined as centrifugal separators, mostly cylindrical of shape, with the in-and outflow of gas along the same axis. Emphasis is laid on features distinguishing swirl tubes from conventional cyclones with tangential entry and a cylinder-on-cone configuration. Design aspects are considered, including the design of the swirl generating vanes, the length of the separation space and the gas and dust outlet configurations. The state of the art for modelling of flowpattern, pressure drop and separation performance are touched upon. After consideration of a few special designs of swirl tubes, some important research challenges for improving swirl tubes are identified.

KEY WORDS: swirl tube; gas cleaning; axial cyclone; vanes; vortex.

INTRODUCTION

The use of centrifugal separators in industry is widespread. They enjoy considerable advantages over filters, scrubbers or precipitators. In conventional cyclones the gas inlet and outlet are at right angles (or close to), giving design problems when space is limited, for instance in the design of compact dedusting units or banks of small centrifugal separators.

For these type of applications, 'axial cyclones' or 'swirl tubes' are often preferred: centrifugal dedusters with the gas in- and outflow along the same axis. Swirl tubes may be 'straight through', with the gas leaving in the same direction as it enters, or 'reverse flow', with the gas reversing direction in the tube, see Figure 1. The body of swirl tubes is often cylindrical as shown, although it may also be of the cylinder-on-cone configuration. In a reverse flow swirl tube, the vanes are arranged annularly around the gas outlet, or 'vortex finder'. The swirling gas flows downwards in the outer region of the separation space, reverses direction low in the tube, exiting through the vortex finder. The dust is centrifuged out and transported along the wall to the dust exit, a slit between the wall and the base plate. Reverse flow swirl tubes may be equipped with a vortex stabilizer¹. In a straight-through, or 'uniflow', swirl tube, the vanes are normally arranged annularly around a central body. The gas swirls downward though the separation space, the particles being centrifuged out to the wall. The gas exits through a central tube, perhaps with an annular base plate, the dust exits through an annular slot.

Apart from compactness, advantages of swirl tubes are quoted as 'lower pressure drop' and 'higher capacity', a disadvantage is 'lower separation efficiency'. It is rarely clear on which basis the comparisons are made. Another advantage is that the flow is more stable, since they are not subject to the disturbances caused by axial asymmetry effects in a tangential gas inlet.

APPLICATIONS OF SWIRL TUBES

Swirl tubes are widely used for dedusting of hot gases. Banks of swirl tubes operating in parallel are used in fluidized catalytic cracking units or after pressurized fluidized bed combustors for the cleaning of the hot, pressurized flue gas. The gas in- and outlets and the

dust outlet are often connected to plenums (see Figure 2) Often banks of small swirl tubes are connected downstream in series with larger conventional cyclones^{3,4,5}.

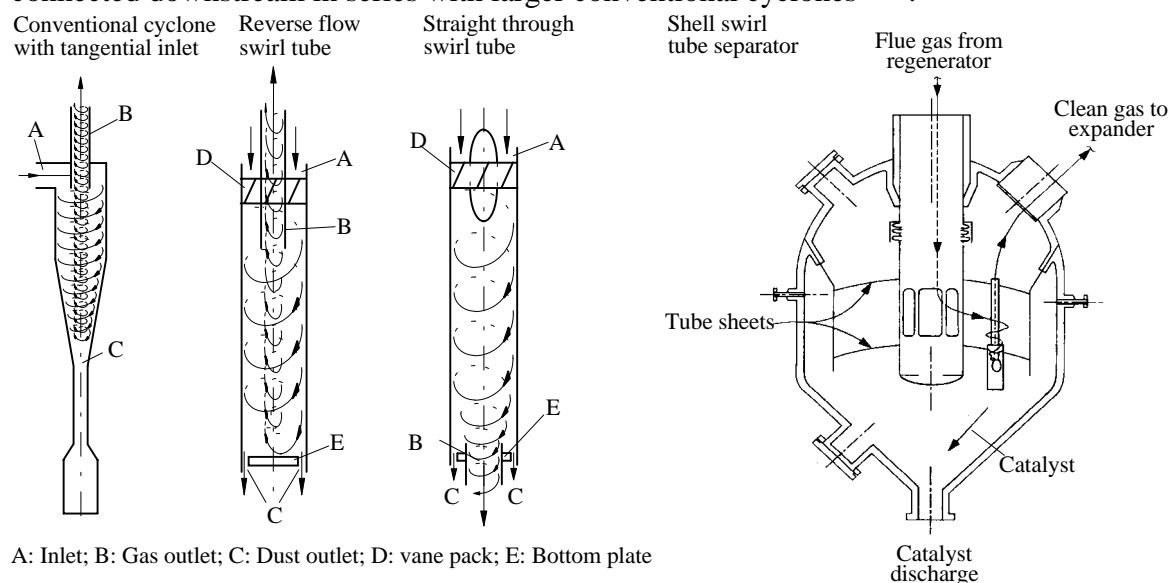


Figure 1 Sketches of centrifugal dedusters Figure 2 Positioning of swirl tubes²

The duty may be the separation of catalyst from reactive gases to minimize unwanted reaction⁵, or the cleaning of exhaust gases before power recovery plant. Here, the emphasis is on the efficiency of separation of particles larger than a critical particle size, which, if left in the gas, will cause erosion of the back edge of turbine blades.

A new application of swirl tubes is for dehydration, separation of oil and water, on off-shore installations or underground where space is limited⁶.

DESIGN ASPECTS

The design of some specific sections is considered separately below. A distinction between reverse flow and straight-through swirl tubes is only made where it is clearly relevant.

GUIDE VANES

For a given throughput and body diameter, the swirl intensity in tangential entry cyclones can be varied by varying the inlet cross-sectional area. In swirl tubes, the vane exit angle, β , is the main determining factor (see Figure 3). Decreasing β increases the swirl intensity, the separation efficiency, and the pressure drop⁷. If β is made too small separation and turbulence generation may occur⁶. Recommended ranges for β are 20-29°⁷, or 15-30°^{8,9}. Spacing so that the ratio u/t in the figure about $\frac{1}{4}$ is recommended in^{8,9}, where the possibility of separation at the leading edge of flat vanes is also indicated, while bent vanes, as shown here, are not subject to this.

Others¹⁰, drew on the literature on fixed vane jet turbines for the design of vanes for a liquid-liquid separator, but do not report their resulting vane geometry.

Vanes may be given different spatial designs. So-called 2-D vanes are simply sheets bent in one dimension as indicated in Figure 3. 3-D vanes are twisted so that, when drawing a line in the plane perpendicular to the cyclone axis along the surface of the vane, the line will always cut the axis. Also the vane orientation may be varied. In⁷ normal orthogonal vanes are compared with 'backwards secant' vanes (see Figure 4). The latter were found to have a beneficial effect in moving the particles towards the outer wall.

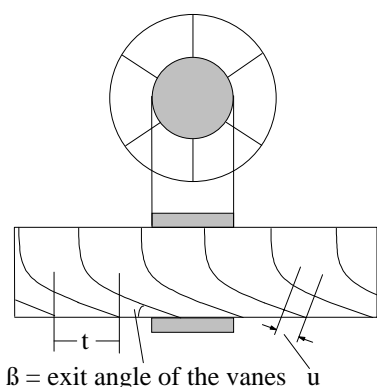


Figure 3 Swirl vanes

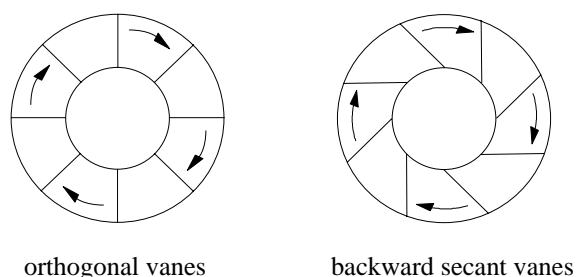


Figure 4 Two swirl vane configurations

LENGTH OF THE SEPARATION SPACE

In cylinder-on-cone tangential entry reverse flow cyclones, the cyclone length is mainly an important design parameter in that the 'end of the vortex' (see below) should neither be within the conical section of the cyclone, nor extend to the bottom of the dust collection hopper, so that dust is reintrained¹¹.

Little information is available about the influence of the length of reverse flow swirl tubes on the separation efficiency.

In straight-through swirl tubes it has been found¹² that doubling the dimensionless length (from vanes to gas exit opening), L/D , with D the body diameter, from 3 to 6 lead to a reduction of separation efficiency. This was attributed to decay of the swirl. A dimensionless length of around 3 was recommended. In another study¹³, concerned with cylindrical straight-through cyclones with tangential inlets the optimal L/D was found to increase from 2 to 3 at 13 m/s tangential inlet velocity to 3 to 4 at 31 m/s. The trend with inlet velocity was attributed to disturbances in the tangential inlet, such should not be present in swirl tubes.

It is well known that if swirl is induced in a fluid flowing along a tube, the swirl decays slowly in an exponential manner in the flow direction^{12,14}. However, particularly if the cross-sectional area increases in the flow direction, the vortex may break down at a particular point in an instability¹⁵. A similar, and probably related, phenomenon is observed in reverse flow gas cyclones: an axial position where the vortex spontaneously turns, referred to as 'the end of the vortex'.^{11,16} The conical section in reverse-flow tangential cyclones seems to stabilize the vortex, while high solids loadings appears to reduce the length of the vortex¹¹.

Such a phenomenon will probably be present in long reverse flow swirl tubes. An expression for the 'natural vortex length' in tangential cyclones is¹⁶:

$$\frac{L}{D} = 2.3 \frac{D_x}{D} \left(\frac{D^2}{ab} \right)^{1/3} \quad (1)$$

where D_x is the diameter of the gas outlet tube, and a and b the height and width of the (rectangular) tangential gas inlet. It is more doubtful whether vortex breakdown takes place in straight-through swirl tubes. The large drop in separation efficiency observed in¹² when doubling the length of their tube, seems more than one might expect from a smooth, exponential decay of the swirling motion¹⁴, and might indicate some anomalous occurrence.

DESIGN OF THE GAS AND DUST OUTLETS

Decreasing the diameter of the vortex finder is known to cause an increase in the swirl velocity in the core of a tangential entry cyclone and an increase in pressure drop and separation efficiency.

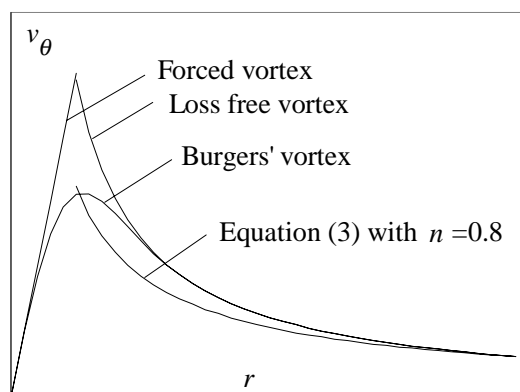


Figure 5 Different vortex laws

For reverse flow swirl tubes an increase in swirl intensity and separation efficiency by increasing the ratio of cross-sectional areas: A_{in}/A_{out} , S is reported ⁷, although the basis for comparison is not entirely clear. The improvement is only for moderate values of S ; recommended values are 2.7-3.3. The shape of the vortex finder is either cylindrical or conical ^{1,7}.

For straight-through swirl tubes, the central body, around which the vanes are placed, is mostly constructed in an aerodynamic shape to minimize disturbances in the flow. The gas exit is a tubular section centrally placed in the separation space, either with or without an annular bottom plate attached near the mouth.

The dust exit in all swirl tubes is an annular slot around the periphery of the base plate or dust exit. In ⁷ three different configurations for reverse flow swirl tubes were investigated: a conventional flat base plate, a plate with a central orifice and without base plate. A central orifice caused the vortex motion to extend to the dust bunker. It nevertheless had a beneficial effect on separation efficiency, stabilizing the vortex motion. The reintrained dust from the bunker was separated again in the separation space anyway. Without base plate the separation efficiency was less good.

FLOW PATTERN, PRESSURE DROP AND SEPARATION PERFORMANCE

FLOW PATTERN AND PRESSURE DROP

In order to calculate the separation performance of the swirl tube, the flow pattern has to be known, so that the forces acting on a particle in the separation space can be estimated.

In conventional reverse flow cyclones the tangential velocity distribution is roughly a quasi-free vortex surrounding a core of quasi-forced swirl. The outer annulus of the vortex has a downwardly directed axial velocity surrounding a core of upwardly directed flow. The radial flow is generally centripetal, causing an inward drag force on the particles.

In cylindrical tubes with swirling water it has been found ¹⁵ that the angular velocity is well approximated by Burgers' vortex (see sketch in Figure 5):

$$v_{\theta} = \frac{K}{r} (1 - \exp[-\alpha r^2]) \quad (2)$$

where K and α are parameters varying slowly in the flow direction and r is the radial coordinate. Figure 5 also shows the vortices to which it converges at low and high r . It has been found in tangential entry cyclones that the outer annulus is considerably less than loss free, and the following vortex law below is preferred (see Figure 5):

$$v_{\theta} = v_{\theta,w} \left(\frac{(D/2)}{r} \right)^n \quad (3)$$

where the index n is less than unity, often around 0.8. Another vortex law has been derived in conventional cyclones based on a moment of momentum balance ¹⁷. This work may be adapted to swirl tubes.

The axial and tangential velocity distributions in a liquid filled model have been measured using laser doppler anemometry ¹⁰. The findings confirm those in ¹⁵ qualitatively. It appears that the core of forced swirl decreases in diameter downstream of the vanes. The velocity distribution in a gas filled swirl tube has been measured with a pitot-tube ⁷ with similar results. Here, Equation (3) was used with an empirical value for n to model the results. In one cyclone, the very low value of $n=0.514$ was found. Empirical relations are also given for the radius of the core of forced swirl and that of upwardly directed axial flow (neither depending on the axial coordinate) and for the distribution of radial velocity.

Another approach to modelling the flow pattern in swirl tubes is computational fluid dynamics (CFD). It is difficult to simulate highly swirling, turbulent, confined flows, an optimal turbulence model has to be found ¹⁸. Once validated, however, CFD offers an alternative way of investigating most aspects of swirl tube operation and design.

The issue of the pressure distribution in centrifugal separators is complicated by the presence of swirl. Dynamic and static pressure are interchanged, for instance static pressure is converted to dynamic pressure when the fluid is accelerated in the vanes ⁶. There is also a strong radial static pressure gradient in a vortex. It is therefore better to consider the sum of the dynamic and static pressure. The drop in this is due to dissipation.

The dissipative loss can be considered separately in: a) the swirl vanes, b) the separation space, and c) the gas outlet. little information as to the loss in the vanes is available. It is stated that in straight-through swirl tubes, most of the total pressure loss is in the vanes ¹⁹, but it is not clear whether this includes the dynamic pressure. In ⁸ the dissipative pressure losses in the separation space and the vortex finder of reverse flow cyclones are considered. The latter is found to exceed the former by a factor of five to ten. Expressions for both are given. An empirical expression for the total pressure drop in swirl tubes is given in ⁷, indicating that it increases with decreasing β (increasing swirl velocity) and decreasing D_x and increases linearly with the square of the inlet velocity, v_i^2 . We obtained a pressure drop some 40% lower when repeating their numerical example.

SEPARATION PERFORMANCE

Models for conventional cylinder-on-cone cyclones can be categorized in:

- Equilibrium orbit models where a critical particle size, or cut size, is determined from a force balance on a particle rotating in the cylindrical surface below the wall of the vortex finder extending to the bottom of the cyclone, considered to be the limit between upward and downward axial flow. The inward drag on the particle is calculated assuming uniform radial gas velocity across this surface.
- Time-of-flight models, where it is considered if a particle has the time to reach the cyclone wall before reaching the bottom of the cyclone, neglecting the radial gas flow. If not, it is swept up in a strong radial inward flow there, and lost.
- Hybrids between the two.

In ⁷ the equilibrium orbit concept is used for reverse flow swirl tubes. We do not give the expression here, the interpretation of a couple of the parameters is not unequivocal from the article. The reader can apply this concept to reverse flow swirl tube consulting ²⁰. It is interesting that in ⁷ no enhancement of the fractional separation efficiency with increasing dust load was seen, although this is a very prominent feature in tangential entry cyclones.

Most modelling of the separation efficiency of straight-through swirl tubes is on basis of the time-of-flight concept, with simple assumptions about the tangential and axial velocity distributions. In ⁶ the following model is proposed:

$$\frac{L_s}{D} = \frac{18\pi^2}{\alpha^2} \frac{1}{Re} \frac{\rho_f}{\rho_p - \rho_f} \left(\frac{\Delta}{(d/2)} \right)^2 \quad (4)$$

where L_s is the length of tube required to separate particles of radius $d/2$, ρ_f and ρ_p the fluid and particle densities, respectively, Re the Reynolds number defined in terms of the mean axial velocity and D . α is a constant depending on the deflection angle, equal to around 4π . This simple model based on potential flow theory does not take into account the attenuation of the swirl along the tube. Another, similar expression has been proposed ¹⁹, but under the assumption that, for an incompressible fluid, the mean resultant velocity just after the vane pack equals the mean axial velocity just before it, violating continuity. The model will have to be corrected for this.

Although the equilibrium orbit models have been very successful for cylinder-on-cone cyclones, the assumption of the radial gas flow being axially uniform may be inappropriate for cylindrical swirl tubes.

SOME SPECIAL DESIGNS

Some special designs of swirl tubes are proposed in the literature:

- Increasing the swirl by generating it in an expansion ⁶. Subsequent decrease of the cross-section in the separation space with cause an increase in the swirl intensity by conservation of angular momentum in the flowing fluid.
- Increasing the swirl by introducing gas tangentially through small tubes, arranged around the circumference of the swirl tube, either above or below the vane pack ¹².
- An apparatus (PoC) for the use of the swirl motion just downstream of a conventional cyclone for extra separation has been proposed ²¹.
- A 'rotary flow cyclone', the swirl being generated by means of a helical screw shape, dividing the cross-section into two semicircles ²².
- A straight-through swirl tube with reverse particle flow ¹⁹. The gas rotates up through the inner part of the separation space, while the particles are centrifuged out into a downward spiralling flow generated by secondary air introduced through tangential tubes arranged around the circumference of the apparatus.

CONCLUDING REMARKS, RESEARCH CHALLENGES

Although some details, such as the length of the separation space and the vane exit vane angle and spacing have been considered in a rough way, models for separation efficiency and pressure drop of swirl tubes as a function of physical dimensions are not available. This leaves the designer with very little to go on except known designs and experimentation. The following experimentation is suggested, using the factorial experiment design where applicable. The three first investigations can be performed in a transparent model without dust present.

- The level of swirl and the dissipative pressure drop over the vanes can be monitored as a function of exit angle and vane spacing using laser-doppler anemometry and static pressure points. Also the presence of vortex breakdown can be investigated (by flow visualization).

- Different types of vanes, for instance 2-D and 3-D, can be compared once for the same exit angle and vane separation to see if 3-D offer any substantial advantages. Swirl enhancement by swirl generation at higher radii ⁶ can be tried out.
- Details about the shape of the vanes, for instance at the leading edge, to avoid separation and turbulence generation can, at least initially, perhaps best be investigated by CFD.
- With dust present, the separation performance and the dissipative pressure drop in the vanes, the separation space and gas outlet should be investigated using an optimal vane design. the length of the separation space, the width of the gas outlet and the inlet velocity and solid loading can be varied. It should be checked whether the backward secant vane configuration ⁷ offers advantages.
- Aspects crucial to the reliability of swirl tubes is their degradation in actual plant, either due to the build-up of deposits on the inner walls or due to wear and eventual failure of the material of construction. This can be investigated experimentally and with CFD.

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SYMBOLS USED

A	Cross-sectional area
a, b	Height and width of (rectangular) gas inlet
D	Diameter
d	Particle diameter
K, α	Parameters in Equation (2)
L	length of separation space
n	Index in Equation (3)
r	Radial coordinate
Re	Tube Reynolds number $\equiv (D \langle v_z \rangle / \nu)$
S	A_{in}/A_{out}
t	horizontal distance between vanes at outer wall
u	distance indicated in Figure 3
v	Velocity
α	Parameter in Equation (2) <u>or</u> parameter in Equation (4)
β	Vane exit angle
ν	kinematic viscosity
ρ	Density

SUBSCRIPTS:

f	Fluid
in	Inlet
out	Outlet
p	Particle
s	Required for separation of given particle size.
w	wall
x	Gas exit
z	In the axial direction
θ	In the tangential direction