Experimental Investigation on Dust Separation Characteristics of a Vortex Tube*

Kap-Jong R Ju**, Jung-soo KIM*** and In-Su CHOI****

Dust separation characteristics of a counter-flow vortex tube were investigated with lime powders whose mean particle sizes were 5 and 14.6 μm. The experiment showed that a vortex tube can be used as an efficient pre-skimmer to separate particles from the waste gas in industry. In case of fine particles, a trend of increasing separation efficiency was observed with inlet pressure up to 180 kPa at which the flow rate was 9.5 m³/hr, but there was a tendency of reduction in the coarse particles. For both powder sizes, the efficiency and the effective nozzle inlet velocity were 93% and 14.52 m/s respectively, while the tested vortex tube had a small diameter of 16 mm and the ratio of the nozzle hole area to the tube cross-sectional area was 0.15. Additionally, the geometric ratios of the vortex tube could be proposed as 0.44 for the ratio of the orifice diameter at clean gas exit to the tube diameter and 14.0 for the ratio of the tube length to the diameter.

Key Words: Vortex, Pollutant, Counter-Flow Vortex Tube, Gas-Solid Separation, Dust Separation Efficiency, Optimum Geometric Ratio

1. Introduction

The removal of pollutants from various effluent streams discharging into the atmosphere has been a major concern in air pollution work for many years; therefore, a tremendous amount of research has been conducted to develop efficient and reliable air control devices. Among the existing devices for waste gas cleaning, cyclones are the most commonly used collectors of solid particles from gaseous streams due to efficient separation, high gas-handling capacity, and temperature independent characteristics(1). However, they are not suitable for dust containing a high proportion of fine particles in the size range below 10 μm(2).

A vortex tube, which might be operated with a similar concept of centrifugal effect to that of the cyclone, was used to separate particulate matter from the exhaust gas of a diesel engine and about 80% of the separation was achieved by Sibbertsen(3). He revealed the possibility of separating fine particles through the vortex tube. Additionally, Choi(4) showed that the separation of about 90% of solid particles from liquid stream was possible by means of a vortex tube.

Since a vortex tube was invented by Ranque(5) and rediscovered by Hilsch(6), it has been used for liquefying gases in early times and gradually researched to get cold and/or hot streams by inducing compressed gases(7,8). Meanwhile, its feasibility as a separator of gaseous mixtures was investigated by Linderstrom-Lang(9), although the separation effect varied only within one to three thousandths of a percent by volume.

Hence, the current study investigated a relatively unexplored application of vortex tube, separation of dust from a stream of air. Furthermore, different ratios of vortex tube geometry, operation velocities, and dust sizes were examined to reveal their influence on separation efficiency.
Nomenclature

$D$: Diameter of vortex tube [mm]
$D_e$: Diameter of orifice at clean gas exit [mm]
$D_a$: Diameter of nozzle hole of vortex generator [mm]
$L$: Length of vortex tube [mm]
$m$: Mass of dust collected at the outlet [kg]
$N$: Number of nozzle [-]
$Q$: Volumetric flow rate [$m^3/s$]
$S_a$: Ratio of nozzle hole area to tube cross-sectional area [-]
$V_{in}$: Gas velocity at the nozzle inlet of vortex generator [$m/s$]
$y$: Volume fraction of clean gas to total dust laden gas [-]
$\eta$: Efficiency of dust separation [-]
$\xi$: Ratio of orifice diameter to vortex tube diameter [-]

Subscript

in: inlet of vortex tube
c: clean gas exit
d: dirty gas exit

2. Separation Mechanism through Vortex Tube

Vortex tubes can be classified into counterflow and uniflow ones according to the flow patterns proposed by Fulton[10] and Comassar[11] as illustrated in Fig. 1(a) and (b) respectively. The flow patterns were visualized by Scheper[12] and Lay[13]. Vortex tubes are attractive for applications because of the feature of no moving parts and their simple form. The vortex tube is a piece of tubing closed at one end by a plug (or opened by orifice) and provided with a tangential inlet nozzle near the plug (or orifice). A gas stream is led into the tube through the jet from a compressed gas source.

For the counterflow vortex tube in Fig. 1(a), both ends of the tube are opened and partly closing the throttle valve at the far end of the tube controls the flow rate. As the compressed gas flows tangentially into the tube, it expands and rotates in the vortex generation chamber. Consequently, the vortex flows are generated, as illustrated in Fig. 2, and they move along the tube. On account of the friction between gas and the tube's inner surface, the angular velocity becomes low in the outer annular region and high in the inner region. Therefore, in the outer region the free vortex is formed by the law of constant angular momentum ($\omega r^2$=constant). As the flow moves towards the throttle valve, it is changed to the forced vortex in the central core. Such a solid body rotation tends to have a uniform angular velocity distribution ($\omega$=constant) due to the viscous effect between adjacent fluid layers.

Meanwhile, the pressure in the central core becomes lower than that in the outer region due to the effect of centrifugal force, and the central region is exposed to the ambient at the orifice side and blocked with the throttle valve at the opposite side. Thus, the flow is reversed in the central core as a result of the inverse pressure gradient near the throttle valve, and the turbulence is intensified. Owing to the turbulence diffusion, dust particles migrate toward the outer radius. Subsequently, the centrifugal acceleration, resulting from the strong rotation of the flow, forces the particles to be slung to the tube wall and moved to

![Fig. 1 Supposed flow patterns through vortex tubes](image)

![Fig. 2 Cross-section of vortex tube showing free and forced vortex flows](image)
the outlet. Thus, the dirty gas containing many dust particles can be discharged through the throttle valve, but the relatively clean gas is moved along the central core and expelled through the orifice.

On the other hand, the uniflow vortex tube has two openings at the same end, so that the reverse flow does not exist, as shown in Fig. 1 (b). The dirty gas flows in the outer annular region and the clean gas does along the inner core.

From the preliminary tests of vortex tubes, the counterflow vortex tube gave a better separation efficiency than the uniflow one did. The performance of the latter remained around 80% and became worse in case of small sized particles. Its characteristics were similar to those of a swirl air cleaner\(^{19}\), which had the same mechanism of separation as a uniflow cyclone. Therefore, the counterflow vortex tube was selected for this work.

3. Experiment

The vortex tube and vortex generator used in this work are schematically shown in Fig. 3. It consists of a tube, a vortex generator in which vortex flow is formed from tangentially induced gaseous stream, an orifice for clean gas exit, and a throttle valve for dirty gas exit. For the convenience of experiments, a small sized vortex tube was tested with an inner diameter (D) of 16 mm, as shown in Table 1. The other dimensions were determined from the geometric ratios based on the tube diameter, although the known ratios gave the best performance on energy separation rather than dust separation. Since the ratio of the nozzle hole area of the vortex generator to the cross-sectional area of the tube (\(S_h/S_t\)) was set at 0.15 to obtain efficient vortex flow\(^{18}\), a vortex generator was chosen with 6 tangential holes of 2.5 mm diameter (\(d_h\)). The tested tube lengths (L) were 112, 224 and 336 mm, because the performance was not varied by the ratio of length to diameter when the ratio was more than 2\(^{15}\). In addition, the orifice diameters of the clean gas exit (\(d_o\)) were set at 3, 7 and 11 mm, to obtain the ratio of orifice diameter to tube diameter (\(\zeta\)) around 0.45, which is known as the best ratio for energy separation\(^{18}\).

Figure 4 shows the experimental setup for dust separation tests. The air was supplied to the vortex tube system by a compressor. Subsequently, the compressed air was filtered to remove impurities and dehydrated to extract moisture that could affect the system performance. The air velocity at the nozzle inlet of the vortex generator was varied from 9.43 to 22.40 m/s and the Reynolds number based on the nozzle hole diameter being from 1511 to 3590, when the air pressure was regulated from 20 to 160 kPa, respectively. The experimental dusts were fed to the vortex tube by a screw type dust feeder with a constant supply of 3 g/Nm\(^3\). Furthermore, the vortex tube was set-up axially to position the exit of dirty gas in the direction of gravitation.

To control the volume fraction of clean air to the total induced air (\(y\)), the throttle valve was used to adjust the flow area and flow rate at the dirty air side. The volume fraction of clean air was varied from 0.1 to 0.9. Bag filters, whose permeable size was 0.3 μm, were installed at the both outlets of vortex tube to capture the dust particles.

Lime powder was chosen as a test material,
Table 2 Physical properties of tested lime powders

<table>
<thead>
<tr>
<th>Property</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean particle size [μm]</td>
<td>5.019</td>
<td>14.60</td>
</tr>
<tr>
<td>Standard deviation [μm]</td>
<td>1.652</td>
<td>1.724</td>
</tr>
<tr>
<td>Relative density [-]</td>
<td>2.97</td>
<td>3.18</td>
</tr>
<tr>
<td>Specific surface area [m²/g]</td>
<td>0.55</td>
<td>0.16</td>
</tr>
</tbody>
</table>

Fig. 5 Particle size distributions of tested lime powders

because it is produced during the distillation process of coke in iron mills. The powder sometimes clogs pipes, so that the removal of the powder is required to re-use off-gases as fuel for boilers. The test lime powders were obtained by sieving particles with 400 and 500 mesh sieve sets, and their properties were measured with a scanning electron microscope and Aerosizer Mech2 of APII production. The particle size distributions of the powder are shown in Fig. 5 and the physical properties in Table 2. The mean particle size is given after numerically analyzing the particle distribution. Hence, the mean particle sizes of tested powders were 5.0 and 14.6 μm with standard deviations of 1.652 and 1.724 μm, respectively.

4. Results and Discussion

Various combinations of the vortex tube geometry were examined in order to find the optimal geometric ratio at different operating conditions. Dust collected in the bag filters at both ends of the vortex tube was weighed after the experiment to evaluate the separation efficiency. Hence, the separation efficiency is the mass ratio of dust collected in the dirty exit to the dust charged to the vortex tube, and is expressed as:

\[ e = \frac{m_d}{m_{c} + m_d} \]  

(1)

Similarly, the clean gas fraction is defined as the volumetric flow rate at the clean exit to the total flow rate of dust–laden gas supplied to the vortex tube.

\[ y = \frac{Q_c}{Q_c + Q_d} \]  

(2)

The air velocity at the nozzle inlet of vortex generator can be calculated from the supplied air flow rate and the nozzle hole area.

\[ v_0 = \frac{Q}{N_d A_4} \]  

(3)

4.1 Effect of clean gas fraction

When the dust–laden air is induced to the vortex tube after the nozzle inlet velocity is maintained at 9.43 m/s, orifice diameter: 7 mm (\( \xi = 0.44 \)), mean particle size: 14.6 μm.

Fig. 6 Efficiency of dust separation at varying clean gas fraction (nozzle inlet velocity: 9.43 m/s, orifice diameter: 7 mm (\( \xi = 0.44 \)), mean particle size: 14.6 μm)

The efficiency does not change significantly until the clean gas fraction reaches 0.5, and the decrease in the separation efficiency is about 5% as the most. As closing the throttle valve reduces the flow area of dirty gas exit, the reversed flow rate toward the clean gas exit increases, so that the friction between the clean and dirty gas streams brings about the turbulence dispersion. Therefore, fine particles can be re-entrained from the dirty gas stream to the clean gas stream as the clean gas fraction increases, which cause a decrease in efficiency.

However, the application of a vortex tube in an industrial dust control system is desirable from an economic point of view to maintain the clean gas fraction as much as possible. Thus, the condition of the clean gas fraction is set to 0.9 hereafter. Furthermore, the tube length at a given operating condition does not affect the efficiency considerably, although the efficiency at the length of 224 mm (14D), which is a little higher than at other lengths.

4.2 Effect of orifice diameter

As the air velocity at the nozzle inlet increases, the separation efficiency decreases gradually as shown
in Fig. 7, when powder of 14.6 μm as a mean particle size is tested at a tube length of 224 mm (14D) and the clean gas fraction is set at 0.9. With a faster nozzle inlet velocity, the tangential velocity of dust-laden gas increases and the dust particles easily immigrate toward the wall by the centrifugal force. The axial velocity along the tube also increases with strengthened intensity of turbulence. Although most of the large particles cannot contact easily with the wall surface due to the viscosity sub-layer, some of them may bump against the wall and be bounced back by the aid of large eddies of wall turbulence. Subsequently, the particles easily collide with one another and relatively large particles can be broken down into finer particles. These are easy to re-entrain into the reversed clean gas stream, which may result in decreasing the separation efficiency as the nozzle inlet velocity increases.

In case of an orifice diameter of 7 mm ($\zeta=0.44$) at the clean gas exit, the separation efficiency is superior to those in other cases of 3 mm ($\zeta=0.12$) and 11 mm ($\zeta=0.69$). Hence, the value of 0.44, as the ratio of orifice diameter to tube diameter, represents the geometry similarity for effective separation of dusts. This result is similar to the case of cyclone, where the optimum diameter ratio of outlet to cyclone has been reported to be 0.5 by Stairmand and 0.4 by Swift.

However, in case of a 3 mm ($\zeta=0.12$) orifice diameter, the exit area is thought to be smaller than the cross-sectional area of the clean gas stream, so that the outer layer of the reversed stream may recirculate near the outlet and interfere with the induced dust laden gas stream. Thus, part of the dust in the induced stream entrains into the clean gas stream, which results in reducing the separation efficiency. On the other hand, an 11 mm ($\zeta=0.69$) orifice diameter may be larger than that required for the clean gas stream, so that some of the induced dust particles can be emitted directly before they are slung toward the tube wall. As a consequence, the diameter of the clean-gas outlet should be the same as that of reversed clean-gas stream to obtain efficient performance.

4.3 Effect of tube length and particle size

Figure 8 shows the variation of separation efficiency based on the nozzle inlet velocity of the vortex tube with different particle sizes when the clean gas fraction is set at 0.9 and the orifice diameter at the clean gas exit is 7 mm ($\zeta=0.44$).

When the mean particle size of the tested lime powder is 14.6 μm, the separation efficiency decreases as the nozzle inlet velocity increases, as shown in Fig. 8(a). As described in section 4.2, the reason is that the saltation effect may be dominant as the nozzle

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**Fig. 7** Efficiency of dust separation at varying nozzle inlet velocity (mean particle size: 14.6 μm, clean gas fraction: 0.9, length of vortex tube: 224 mm (14D))

**Fig. 8** Efficiency of dust separation at varying nozzle inlet velocity (clean gas fraction: 0.9, diameter of clean gas exit: 7 mm ($\zeta=0.44$))
inlet velocity increases. Generally, the particles collected at the clean-gas exit are expected to be finer than the mean particle size, but a few large particles bounced from the dirty gas stream can be found in the clean gas exit. Figure 9 shows the microphotograph of large particles collected at the clean-gas exit when the tested particle size is 14.6 μm. The photograph was taken by SEM (Scanning Electron Microscope) with gold coating of the powder. The line represents 10 μm as indicated at the bottom of the photographs.

When different lengths of vortex tube are compared, a 224 mm tube length (14D) shows somewhat higher separation efficiency than 112 mm (7D) and 336 mm (21D) in the range of tested nozzle inlet velocity. In case of a 112 mm tube length, the dust-laden gas is forced toward the exit before it can be separated sufficiently into the streams of clean and dust-laden gases, although the ideal flow pattern in a counterflow vortex tube should be the one shown in Fig. 1(a). Thus, some of the dust particles cannot enter the dirty gas stream, but remain and are emitted with the clean gas stream. If the tube length is as long as 336 mm (21D), dust separation can occur in the same manner as that in 224 mm length (14D). Because the interference surface between the clean and dirty streams increases, some of the particles slung to the dirty stream may be re-entrained into the clean gas stream. Dust separation at a counterflow vortex tube might occur in the recirculation region between the inlet nozzle and stagnation point on the axis, as illustrated in Fig. 1(a). Beyond the stagnation point, no further useful separation is possible, because the two streams already have been split. Thus, profiles taken part way along the tube near the stagnation point would give a lower bound on the separative effect, whereas profiles from near the inlet plane would produce an upper bound.

Unlike a 14.6 μm as a mean particle size, separation efficiency increases with the nozzle inlet velocity when a 5 μm powder is tested, as shown in Fig. 8(b). This may result from the agglomeration of fine particles, as suggested by Abrahamson [39]. As the nozzle inlet velocity intensifies, the particles are accelerated with their intensified random motion, so that they can be agglomerated with one another and then slung toward the wall by the strengthened centrifugal force. Thus, the fine particles agglomerated to larger sizes are emitted to the dirty gas exit and many of them are larger than the mean particle size. Figure 10 shows a microphotograph of agglomerated particles collected at the dirty exit when the tested particle size is 5.0 μm.

As mentioned in the case of 14.6 μm, the saltation of large particles can occur if the tube length is as short as 112 mm (7D). Thus, the efficiency does not increase as much as that of 224 mm (14D). If the tube length is so long as 336 mm (21D), the separation efficiency increases in accordance with the nozzle inlet velocity, but it does not reach that of 224 mm. As the tube length increases, the interference surface between two streams becomes wider and consequently finer particles can be re-entrained to the clean gas stream. Therefore, the geometry of the vortex tube should be chosen to obtain the best performance of dust separation.

For the same geometry of vortex tube except the length, the effective nozzle inlet velocity is defined as the velocity that can give the same efficiency of separation with both sizes of dust. Hence, the effective

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**Fig. 9** Microphotograph of bounced large particles at clean gas exit (clean gas fraction: 0.9, diameter of clean gas exit: 7 mm (ζ=0.44), tube length 224 mm (14D))

**Fig. 10** Microphotograph of agglomerated particles at dirty gas exit (clean gas fraction: 0.9, diameter of clean gas exit: 7 mm (ζ=0.44), tube length: 224 mm (14D))
Fig. 11 Separation efficiency and effective nozzle inlet velocity versus ratio of tube length to diameter (clean gas fraction: 0.9, diameter of clean gas exit: 7 mm \( (\xi=0.44) \))

nozzle inlet velocity means the crossing points of lines drawn in Fig. 8(a) and (b) at the same tube length. These are 14.52 m/s, 15.65 m/s, and 17.09 m/s when the tube lengths are 224 mm \((14D)\), 112 mm \((7D)\), and 336 mm \((21D)\), respectively. Figure 11 shows the dust separation efficiency and the effective nozzle inlet velocity in terms of the ratio of tube length to diameter.

If industrial waste gas contains dust particles ranging from 5.0 \( \mu \text{m} \) to 14.6 \( \mu \text{m} \) as a mean particle size, the best efficiency of dust separation can be obtained with the least effective velocity at the nozzle inlet when the ratio of length to diameter of vortex tube is about 14. As the particle size becomes larger, lower nozzle inlet velocity may be possible. Additionally, the effective nozzle inlet velocity can be considered as a reference design point, when a vortex tube is applied to the dust control system as an efficient pre-skimmer.

5. Conclusions

The experiment has demonstrated the feasibility of the application of a vortex tube to a dust control system. Using a vortex tube with a 16 mm inner diameter, some parametric studies have been carried out. Since the vortex tube used for the experiments was much smaller than needed for industrial application, further experiments with larger diameter vortex tubes are recommended to accommodate a large scale waste gas system. However, vortex tubes could be used with considerably high efficiency of dust separation.

By means of a small vortex tube, more than 90% of lime powder was separated when the volume fraction of clean gas to the induced dust-laden gas was controlled at 0.9. When the gas velocity at the nozzle inlet was from 9.43 to 22.40 m/s at an operating pressure at the inlet of vortex tube from 20 kPa to 160 kPa, the dust separation efficiency tended to decrease in case of 14.6 \( \mu \text{m} \) mean particle size, but the efficiency increased in 5.0 \( \mu \text{m} \) powder. As the best condition for both sizes of lime powders, the dust separation efficiency and the effective nozzle inlet velocity were shown as 93% and 14.52 m/s, respectively.

To obtain such an efficient performance in dust separation, the geometric ratios of vortex tube are proposed as 0.44 for the ratio of orifice diameter at clean gas exit to the tube diameter and 14.0 for the ratio of tube length to diameter, while the ratio of nozzle hole area to tube cross-sectional area is about 0.15.

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References


