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Recent Research and Development on Aerosol Cyclones-Review

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Abstract

In this paper, Various aerosol cyclones that are developed recently from Kwangju Institute of Science and Technology (KJIST) for increasing collection efficiency or for decreasing pressure drop are reviewed. For the first time, new sets of experimental data are reported on the particle collection efficiency of cyclones with modified surface bodies namely, spiral guide body, circumferential groove body, and vertical groove body. Multi-cylinder cyclones by adding one or two additional cylindrical walls into the conventional cyclone are also described. As an attempt to increase the collection efficiency of small particles, electrocyclone using an externally applied electric field was designed and operated. In addition, factors affecting the cyclone performance were studied including flowrate, body and outlet sizes, cyclone dust outlet, and gas property.

Key words : spiral guide cyclone, double cyclone, triple cyclone, electrocyclone

1. INTRODUCTION

Cyclones are devices that employ a centrifugal force generated by a spinning gas stream to separate particles from the carrier gas. Their simple design, low maintenance costs, and adaptability to a wide range of operating conditions such as sizes and flowrates make cyclones one of the most widely used particle removal devices. Small cyclones are used to collect particles in the field of air pollution control for ambient sampling, while large cyclones are used to remove particles from industrial gas streams. Cyclones are particularly well suited for use under high temperature and pressure conditions because of their rugged design and flexible component materials. The most common cyclone design has a tangential inlet and reverse flow. It is generally known that the flow consists of a double spiral: the outer spiral moving down toward the particle collecting cup and the inner one moving up toward the exit tube.

A number of variations and modifications to the basic design can improve collection efficiency or reduce the pressure drop. Some of these modifications involve a scroll or helix-like inlet instead of the tangential duct. Other modifications that have been proposed include changing the shape of the gas outlet duct or the dust outlet hopper design, as well as the insertion of various kinds of internal vanes. Proposed modifications in the operation include using two or more cyclones in parallel, or in series; recycling a portion of the gas outlet stream back to the feed; using a secondary air stream; and electrifying the cyclone to set up a

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radial potential gradient to augment the collecting force.

The purpose of the present study is to describe recent research and development on aerosol cyclones investigated at Kwangju Institute of Science and Technology. In order to increase particle collection efficiency and decrease pressure drop, various modifications of cyclones are recently investigated. The present study introduces and describes the characteristics of spiral guide body cyclones and groove body cyclones.

As an effort to increase particle collection efficiency and to overcome some of the limitations of conventional cyclones, multi-cylinder cyclones and electrocyclones are also introduced. Finally, the factors affecting the particle collection efficiency are explained and summarized.

2. MODIFIED BODY CYCLONES

The dimensions of a conventional cyclone are shown in Fig. 1. The cyclone has a rectangular inlet and circular outlet. The only difference between the conventional cyclone and other cyclones is that the latter have modified bodies. The crosshatched part shown in the figure, which is referred to as the cyclone body, is replaced with the spiral guide body, circumferential groove body, or vertical groove body. Figure 2 schematically shows the diagram of the modified cyclone bodies. The spiral guide, measuring 4 mm in width and 1.5 mm in depth, was set inside the cyclone body as shown in Figs. 2(a) and (b), respectively, for 4-revolution and 6-revolution spiral guide bodies. Figs. 2(c) and (d) show the circumferential groove and vertical groove bodies, respectively. All grooves measure 2 mm both in width and in depth. The particle collection efficiency for a conventional cyclone has been measured. Then the performance each modified body cyclone is compared with that of the conventional cyclone in order to evaluated the feasibility of these modifications.

2. 1 Spiral guide body cyclone

Two cyclone bodies with spiral guides were fabricated: a four-revolution spiral guide body that induces particle-laden gas to make four revolutions (Fig. 2[a]), and a six-revolution spiral guide body that induces particle-laden gas to make six revolutions (Fig. 2[b]). In order to examine the role of a spiral guide, Figure 3(a) was prepared to compare the collection efficiencies of two spiral guide cyclones and the conventional cyclone at 15 L/min. Graph indicates that the spiral guide plays an important role in enhancing collection efficiency at relatively low flowrates. The six-revolution spiral guide cyclone has the highest collection efficiency, while the conventional cyclone turns out the worst performance. At relatively high flowrates, however, the spiral guide no longer helps in increasing collection efficiency as shown in Fig. 3(b). The collection efficiencies of the three cyclones tested are

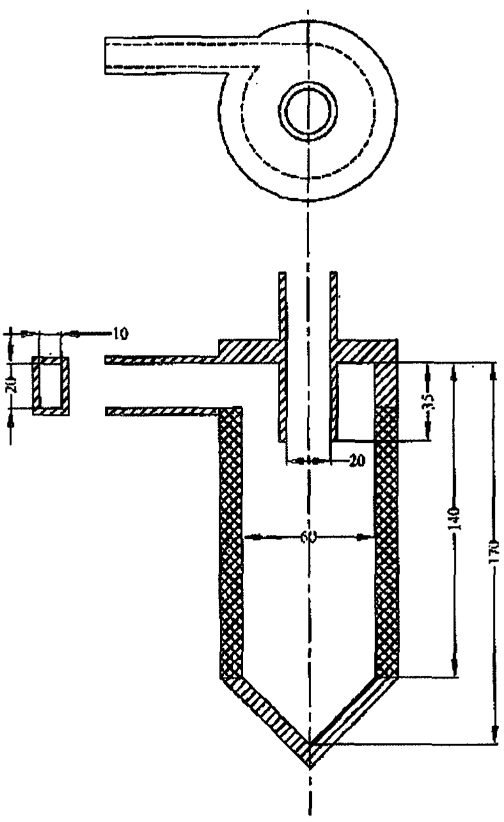


Fig. 1. A schematic diagram to depict conventional cyclone dimensions (unit: mm).

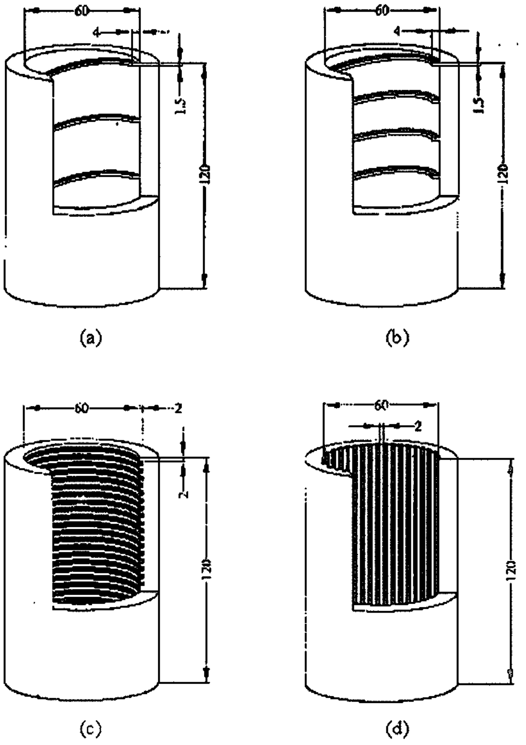


Fig. 2. Schematic diagrams of modified cyclone bodies: (a) Four-revolution Spiral Guide, (b) Six-revolution Spiral Guide, (c) Circumferential Groove, and (d) Vertical Groove (All units: mm).

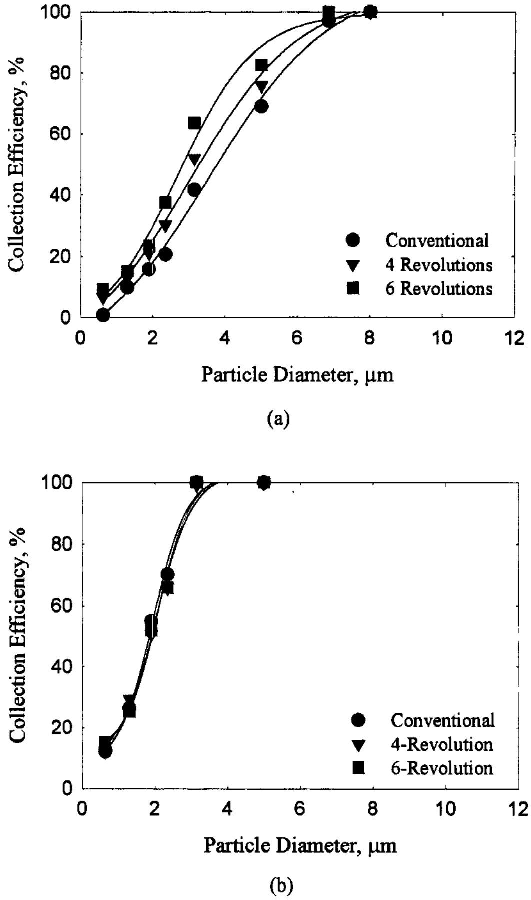
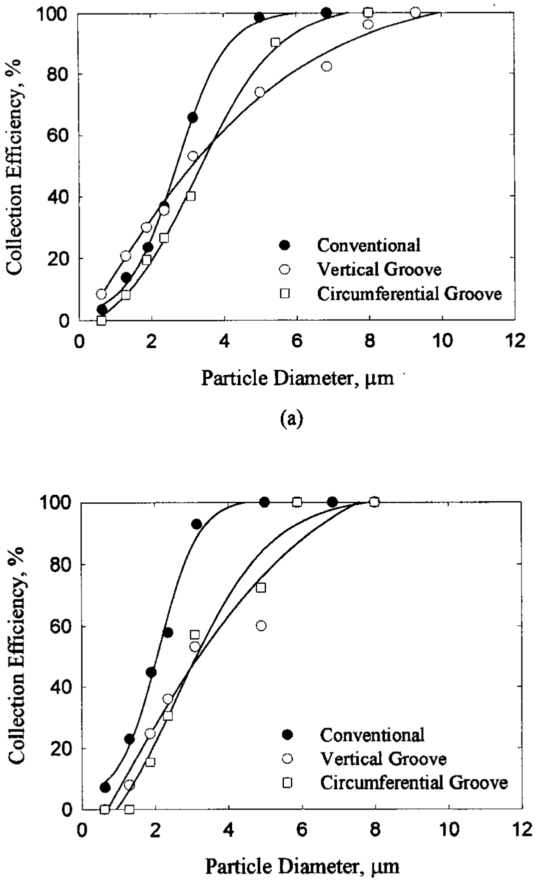


Fig. 3. A comparison of conventional cyclone with spiral guide body cyclones at flowrates of (a) 15 and (b) 80 L/min.

very much alike at 80 L/min.

2. 2 Groove body cyclone

Grooves were hollowed out circumferentially and vertically on the cyclone walls as shown in Figs 2(c) and (d), respectively. Fig. 4 compares the collection efficiency of the groove body cyclones with that of the conventional cyclone. In Fig. 4(a), at a flowrate of 40 L/min, the circumferential groove body cyclone revealed low efficiency for most particle diameters. However, the vertical groove body cyclone has high efficiency for particles smaller than 50% cut diameter. For larger particles, the vertical groove body cyclone posted low efficiency. It is also noted from Fig. 4(b) that at flowrate of 65 L/min, both of the vertical and circumferential groove body cyclones manifested low efficiency for most particle diameters compared with that of the conventional cyclone. The exact mechanisms of the removing particles are not fully understood because of the complex three-dimensional flow in the groove body cyclones, but it is believed that due to the grooves on the cyclone wall, the velocity profile in the cyclone may change. The change in the tangential velocity may be significant. Thus, the efficiencies of the groove body cyclones decrease. The pressure drop is also reduced. Wang and Ye (1999) studied the effect of the thin stick inserted into a cyclone separator on the pressure drop. They found that the thin stick considerably reduced the pressure drop while the total separation



(a)

(b)

Fig. 4. A comparison of conventional cyclone with groove body cyclones at flowrates of (a) 40 and (b) 65 L/min.

efficiency was only affected slightly. However, it was also found that the grade efficiency curve of the cyclone with the stick crossed the curve without the stick.

3. MULTI-CYLINDER CYCLONES

3. 1 Double cyclone

A double cyclone adds an extra cylinder wall into a conventional reversed flow cyclone. Zhu *et al.* (2000) first conceived, fabricated and tested the double cyclone. Fig. 5 shows the detailed design dimensions of the double cyclone. The particle-laden air enters the double cyclone tangentially on the top part of the cylinder and forms a downward vortex along the cyclone wall surface. When the vortex reaches its end, air then flows upward in the annular space between the exit tube that faces down and the cylinder wall to the top of the cyclone. Since there is no way for air to escape at the apex of the cone, it finally flows down again, and escapes through the exit tube. Thus, instead of the traditional two vortexes, the new design incorporates three vortexes in one cyclone design. Particles may be collected on the surface of both cyclone wall and cylinder wall due to the strong centrifugal force generated by the vortexes.

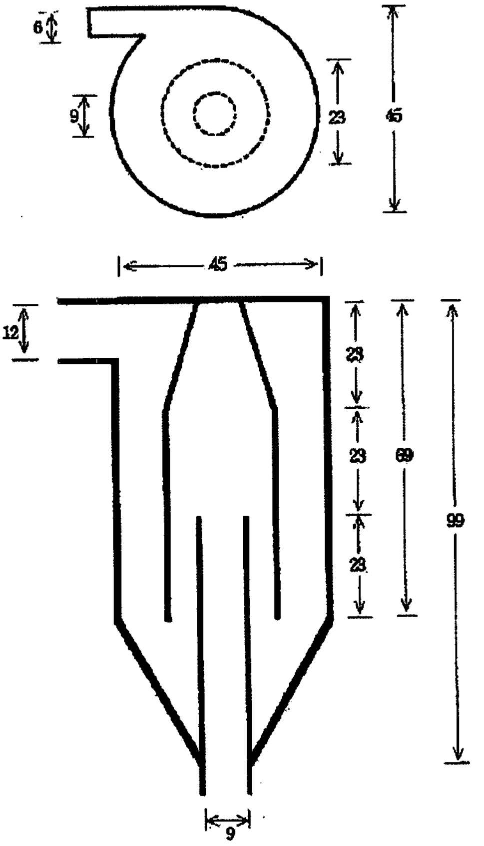


Fig. 5. Double cyclone dimensions (Zhu *et al.*, 2000; unit: mm).

Zhu *et al.* (2000) evaluated the performance of the double cyclone by comparing the particle collection

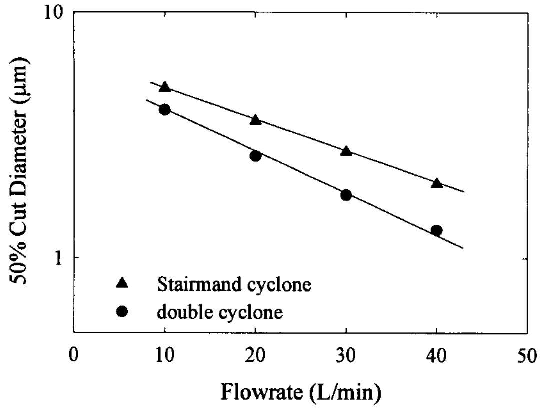


Fig. 6. A comparison of cut sizes for the double cyclone and the Stairmand cyclone at different flowrates (Zhu *et al.*, 2000).

efficiency of the double cyclone with that of a high efficiency Stairmand cyclone, which is also the conventional cyclone. It should be noted that all dimensions of the Stairmand cyclone were different from the double cyclone. They have different body, inlet and gas outlet sizes. Fig. 6 is generated to depict cut sizes versus all tested flowrates for both the double cyclone and the Stairmand cyclone. For all four flowrates, the cut sizes for the double cyclone were consistently much smaller than those of the Stairmand design. In addition, the difference became more and more significant as the flowrate increased indicating that the double cyclone provided higher collection efficiency than the Stairmand cyclone especially at relatively high flowrates.

All of these advantages are due to the added cylinder wall in the double cyclone design that separates the limited cyclone body space into two annular sections and forces the particle-laden air to travel three vortexes before it leaves the cyclone.

3. 2 Triple cyclone

Xiang (2000) extended the idea of the double cyclone design to the so-called triple cyclone, which was formed by adding one more cylinder into the double cyclone. Ideally, it is expected that four vortexes can be produced in a triple cyclone resulting in improved particle separation characteristics. For the purpose of evaluating the performance of triple cyclone, three cyclones which were a conventional cyclone, a double cyclone and a triple cyclone were constructed with glass. All the three cyclones of different structure have the same body diameters and identical inlet and gas outlet sizes. It is clear from Figure 7 that the efficiency data for both triple and double cyclones can be roughly accommodated to the so-called “S” shape as for the conventional cyclone and that the collection efficiency increases as either flowrate or particle size is increased. However, at both flowrates, the efficiency curves for the double cyclone are positioned to the right of those curves for the conventional cyclone indicating that the collection efficiency of the double cyclone is lower than that of the conventional cyclone. If the efficiency curves for the triple cyclone are examined, it is obvious that the triple cyclone has the lowest collection efficiency among the three different designs. This result is completely opposite to what has been expected. In a double cyclone, the existence of the additional cylinder separates the whole inner space into two annular sections. In triple cyclone, three annular sections exist. Ideally, it is expected that one more vortex will be produced in the double cyclone than that in the conventional cyclone and that one more vortex will be produced in the triple cyclone than that in the double cyclone because the gas streams are forced to travel all the annular sections inside a cyclone. Since the particles entrained in the gas streams will experience the centrifugal force for a longer time due to the existence of the additional vortexes, the highest collection efficiency is expected to be achieved on the triple cyclone. However, it is not true as can be seen from Fig. 7.

Although it is not possible to exactly explain the poor performance of the double and triple cyclones due to the lack of knowledge of flow within them, the following reasons are identified with reference to the working principles of the conventional cyclone. Kim and Lee (1990) experimentally studied the effects of the cyclone body diameter and the gas outlet size on the

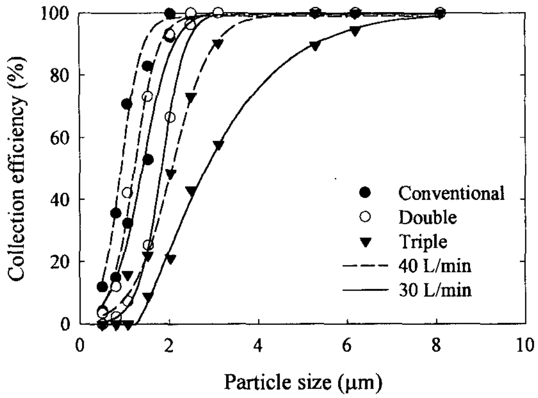


Fig. 7. A plot of collection efficiency as a function of particle size for conventional, double and triple cyclones (Xiang, 2000).

conventional cyclone performance, and found that the collection efficiency increased as the gas outlet diameter became smaller. They explained this trend by that a small gas outlet favored the formation of a well-defined sharper spiral flow. Leith (1984) also discussed the effects of gas exit tube and pointed out if the gas exit was large relative to the body diameter, wall effect might hinder the formation of the vortex. In the double cyclone, the additional cylinder can be regarded as the exit of the first stage. It is apparently larger than the gas exit in the conventional cyclone. Thus the vortex in the first annular space of the double cyclone cannot be well formed and will contribute less to the particle collection than that in the conventional cyclone. The situation in the triple cyclone is even worse due to the larger additional cylinder.

4. ELECTROCYCLONE

In an electrocyclone, when high voltage is applied to the discharging wire as shown in Fig. 8, a number of gas ions are generated in the space, creating an electric field. These gas ions charge the particles like the working principle of the electrostatic precipitator. The particles are collected and deposited on the cyclone body wall by centrifugal force, which is the main force in conventional cyclones, and electrostatic force, which is the main energy in the electrostatic precipitator. The combination of these forces yields high particle collection efficiency, particularly for small particles of dielectric materials. The electrocyclone's particle trajectories and the mechanisms of removing particulates are more complicated than those of conventional cyclones, which is one reason why not many studies on electrocyclones have been carried out. Dietz (1982) enhanced the cyclone separator by using electrical force and Plucinski *et al.* (1989) applied high voltage to the vortex finder instead of the central wire for charging particles. Cheng and Wang (1999) also experimented on the particle collection efficiency of electrocyclone containing a central wire.

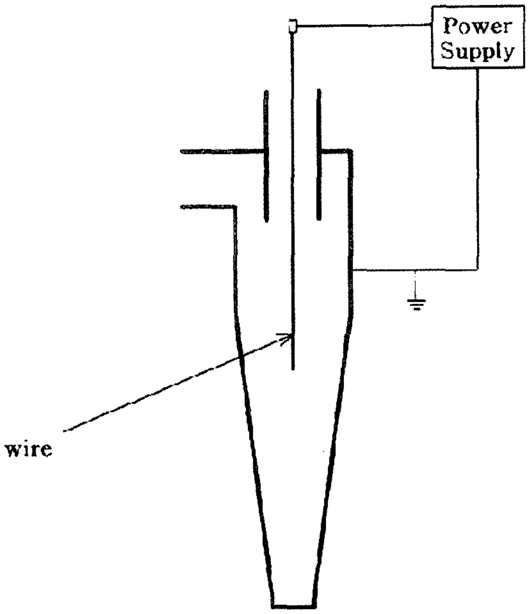


Fig. 8. A schematic diagram of electrocyclone with electrode.

The applied voltage affects the spatial distribution of the current density, electric field, and space ion density. Therefore, the electrocyclone yields different characteristics of collection efficiency according to the applied voltage. When the applied voltage increases, the collection efficiency of the electrocyclone also increases as shown in Fig. 9, particularly for small particles. The slope of particle collection efficiency in a conventional cyclone is steep because only large particles are collected by centrifugal force and the collection efficiency of small particle size range is very low. However, when the voltage is applied to the discharge wire, small particles are collected by electrostatic force and the slope of collection efficiency is flatter.

Other factors affecting electrocyclone performance are discharge wire diameter, length of vortex finder, length of discharge wire and corona discharge. The diameter of the discharge wires plays an important role in determining the electrocyclone's performance. As the wire diameter is increased, the collection efficiency tends to decrease because increasing the diameter of the corona discharge wire leads to higher corona starting voltage, low electric field intensities at the surface of the wire, and a reduced corona current. In the vortex finder, the collecting principle in electrocyclone is the same as that found in an electrostatic precipitator because electrostatic force is the main force in the vortex finder. Increasing the length of the vortex finder prompts the collection efficiency of the electrocyclone to improve significantly. Longer discharge wires prompt the current to converge at the bottom of the cyclone while the magnitude of the current is increased because the lower part of the cyclone is a circular cone. This converged, increased current improves collection efficiency and many particles are collected in the vortex finder and at the bottom of the cyclone. Positive and negative corona discharges have quite different properties and appearances in an electrocyclone. The collection efficiency of an electrocyclone in negative corona discharge is higher than that in positive corona discharge.

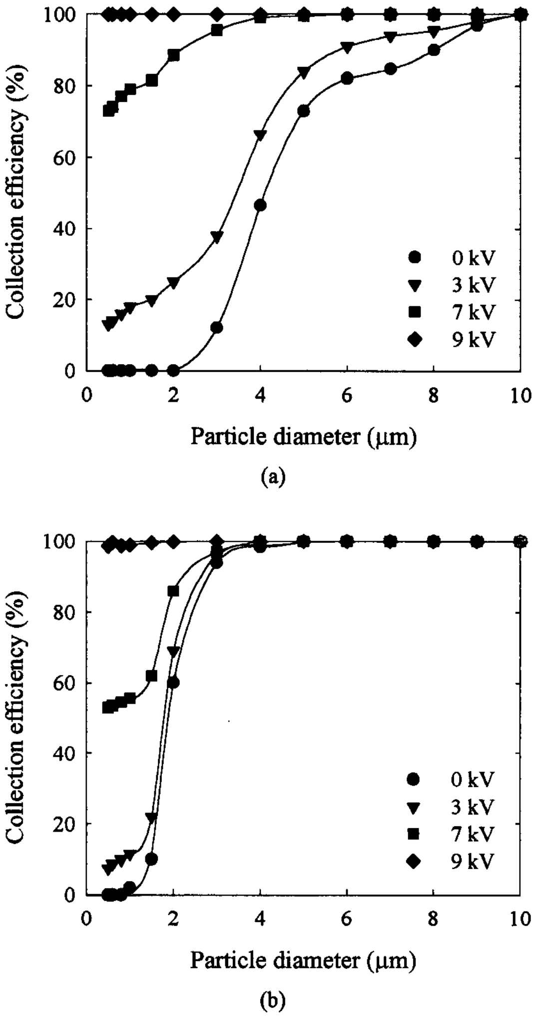


Fig. 9. A plots showing the effect of applied voltage on collection efficiency of electrocyclone at flowrates of : (a) 60 and (b) 120 (Lim *et al.*, 2000).

5. FACTORS AFFECTING CYCLONE PERFORMANCE

5. 1 Flowrate

Most experimental studies showed that the collection efficiency increases with flowrate and that for any flowrate, the efficiency increases with particle diameter (Zhu and Lee, 1999; Iozia and Leith, 1990; Kim and Lee, 1990; Moore and McFarland, 1990; Dirgo and Leith, 1985; Lee *et al.*, 1985). Figure 10 shows the collection efficiency increases significantly with increasing either particle size or the gas flowrate. Higher flowrate caused higher inlet velocity and reduction in the cut size. It should be noted that an increase in the flowrate by less than twofold (from 60 L/min to 110

L/min) can result in the cut size decrease of fivefold at relatively high flowrate. Contrary to conventional idea that cyclones are not suitable for removing particle smaller than 5 μm, this figure shows that at high flowrates, the cyclone has an ability to collect particles whose diameters are much smaller than 5 μm. However, in an electrocyclone, the collection efficiency for small particles increases with decreasing flowrate because the retention time for the particles becomes long in a cyclone and particles have more chances to become charged and collected.

5. 2 Body and outlet sizes

In order to investigate the effects of cyclone body size and gas outlet size on collection efficiency, many studies were performed experimentally (Iozia and Leith, 1990; Kim and Lee, 1990; Buttner *et al.*, 1988; Dirgo and Leith, 1985; Leith, 1984; Smith *et al.*, 1979). If all other dimensions are held constant, an increase in cyclone body size results in an increase in particle collection efficiency. However, if the body size is increased excessively relative to the gas outlet size, the collection efficiency ceases to increase or even decreases somewhat. The gas outlet size is one of the important dimensions affecting cyclone performance significantly. Particle collection efficiency increases as the outlet size becomes smaller. It is believed that the outlet size plays a critical role in defining the flow field inside the cyclone, including the pattern of the outer and inner spiral flows.

5. 3 Cyclone dust outlet

Cyclone dust outlet dimension, which is referred to as cone dimension, plays a role in determining cyclone collection efficiency. Xiang *et al.* (2000) tested three different cyclones to examine the effects of the cone dimension on cyclone performance characteristics. All dimensions were made constant for the purpose of specifically examining the effects of the cone dimension. The only difference among three cyclones is that they have different cone dimensions. The cone dimensions of Cyclones I, II and III are 19.4 mm, 15.5 mm and 11.6 mm, respectively. Fig. 11 was prepared showing the efficiency curves for all three cyclones in one single graph. Obviously, the collection efficiency for a cyclone with a smaller cone opening is higher than that for a cyclone with a larger cone opening. This indicates that the gas and particles are definitely accelerated in the cone section due to the gradually reduced cross-section area. A small cross-section area results in higher tangential velocity and greater centrifugal force acting on particles in the gas stream. Thus, particle collection is enhanced.

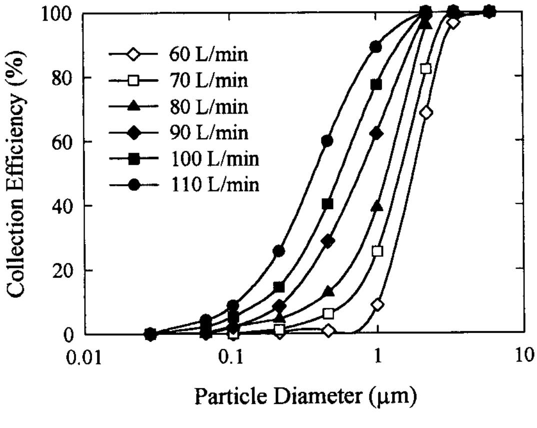


Fig. 10. A plot of collection efficiency as a function of particle size at different flowrates (Zhu and Lee, 1999).

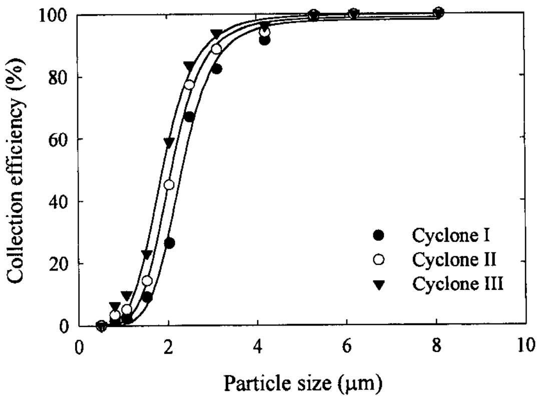


Fig. 11. A plot of the effects of cone dimension on the cyclone performance at 40 L/min (Xiang *et al.*, 2000).

5. 4 Gas property

Most of the existing data were obtained by measuring cyclone efficiencies in a given gas which was usually air (Saltzmann and Hochstrasser, 1983) and then the temperature or the pressure was varied (Parker *et al.*, 1981; Smith *et al.*, 1979). Lee *et al.* (1984) employed two different gases that were air and argon to study the effects of the gas properties on cyclone performance. They found that the density appeared to be an important gas property in addition to the gas viscosity in determining particle collection in cyclones. While high viscosity tends to retard the cyclone performance, a high-density gas is found to enhance the cyclone performance.

6. DISCUSSIONS AND CONCLUSIONS

Recent research and development on aerosol cyclones are described. Conclusions based on the present study can be summarized as follows:

1. The spiral guide, which was set inside the cyclone body, plays an important role in enhancing collection efficiency at relatively low flow rates. However, it no longer helps increase collection efficiency at high flow rates.

2. The experimental results of two cyclones whose bodies were grooved, respectively, vertically and circumferentially show that groove body cyclones are not recommended as a means of increasing particle collection efficiency. No matter how the cyclone body is grooved, grooves may cause turbulent flows to prevent particle-laden gas from spiraling. However, the grooves on the cyclone wall reduce the pressure drop.

3. In case of multi-cylinder cyclone, if cyclones of different structure had the same body diameters and identical inlet and gas outlet sizes, the triple cyclone turned out to be the worst design. In addition, the double cyclone was found not better than the conventional cyclone of the same overall dimensions in terms of particle separation. It is believed that non-swirling flow or the weak swirling flow formed in the additional annular spaces attributes to poor performance of the double cyclone and triple cyclone.

4. In an electrocyclone, voltage affects the spatial distribution of the electric field, space ion density, and current density. Thus collection efficiency is affected by different factors. As the applied voltage is increased, the collection efficiency also increases.

5. The collection efficiency increases significantly with increasing either particle size or the gas flowrate, with increasing cyclone body size if all other dimensions are held constant, with decreasing gas outlet size, and with decreasing cone opening. While a high-viscosity gas tends to retard the cyclone performance, a high-density gas is found to enhance the cyclone performance.

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에어로졸 싸이클론에 관한 최근 연구 고찰

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초록

본 연구에서는 싸이클론의 입자 제거 효율을 향상시키고 압력 손실을 줄이기 위해 최근에 수행된 여러 연구들을 중심으로 고찰하였다. 싸이클론 내부에서 형성되는 나선흐름을 가이드를 설치하여 유도하는 나선흐름 유도 싸이클론, 싸이클론 내부에 한 개 또는 두 개의 실린더를 추가로 설치한 이중 또는 삼중 싸이클론 및 싸이클론의 장점과 전기 집진기의 장점을 접목한 전기 싸이클론을 종합적으로 고찰, 검토하였다. 이러한 싸이클론의 효율을 결정짓는 주요한 인자로는 유량, 싸이클론 및 가스 유출구의 크기, 제거 입자 배출구의 크기 및 싸이클론 내부로 유입되는 가스의 점성 및 밀도 등이 있다.

주제어 : 나선흐름 유도 싸이클론, 이중 싸이클론, 삼중 싸이클론, 전기 싸이클론