

A study on the optimal design of a cyclone system for vacuum cleaner with the consideration of house dust[†]

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Abstract

Cyclone, a type of particle collector widely used in the field of ambient sampling and industrial particulate control, is the principal type of gas-solids separator that use a centrifugal force. The goal of this study is to transform conventional cyclone into a new type of cyclone that can be used for the household vacuum cleaners. To meet the goal, first, the analysis about local environment and dust is carried out. Second, it must have enough high-efficiency not to reduce suction power due to clogging of exhaust filter unit. Two single cyclones with central-hopper-dust-outlet and side-wall-dust-outlet and a twin cyclone are designed and fabricated to evaluate, and compare, their dust collection efficiencies and pressure drops. The measurements of separation efficiency for dust by using DMT test dust type 08 are carried out. House dust experiment is additionally performed to check the local matters applicability such as tissue papers, fur and hairs. The collection efficiency of the twin cyclone is found to be 3–6% greater than those of two single cyclones with the same body diameter, inlet and inner cylinder diameter. Twin cyclone with a large body diameter, a small inner cylinder diameter, a short inner cylinder, a narrow inlet has high separation efficiency. This result indicates the possibility of achieving higher collection efficiencies with a twin cyclone.

Keywords: Twin cyclone; House dust; DMT; Dust collection efficiency; Vacuum cleaner

1. Introduction

A large amount of our time is spent in houses, workplaces, or other buildings; therefore, indoor spaces should be comfortable both emotionally and hygienically. But indoor air contains more than twice the pollutants of outdoor air because of air tightness, poisonous chemicals, food smells, and ticks which are generated by the use of new materials and equipment in buildings. A vacuum cleaner is a representative home appliance for removing harmful materials from floors or carpets. The commercial vacuum cleaners used in houses consist of the paper filter, pre-filter, and exhaust filter through which the clean air discharges to the atmosphere. Though vacuum cleaners are convenient in use, the suction pressure decreases rapidly in proportion to the time of cleaning, and the paper filter also should be replaced periodically due to pressure drops, odors, and bacteria by the residual dust inside the paper

filter [1–4]. And some researchers have designed and tested cyclone for applying to vacuum cleaner [5].

Indoor dusts are affected directly by atmospheric aerosols and many fibers, which are separated from carpets, clothes, bedclothes, papers, and fur of pets, are contained additionally. Most indoor dusts from floors and carpets are coarse particles larger than 2 μ m and these particles can be removed easily using inertial forces. Generally, cyclones are used to collect coarse particles effectively by using centrifugal force which is a kind of inertial forces.

Then the house dust inhaled into the vacuum cleaner has a different size distribution with that of atmospheric aerosols. This study analyzed the house dust inhaled into the vacuum cleaner and carried out the performance evaluation of cyclone system by using DMT (Deutsche Montan Technologie) test dust type 08 and house dust. And two single cyclones with central-hopper-dust-outlet and side-wall-dust-outlet and a twin cyclone are designed, and evaluated their collection efficiencies.

The study of conventional cyclone is focused in the collection efficiency of only fine dust. But there were not only fine

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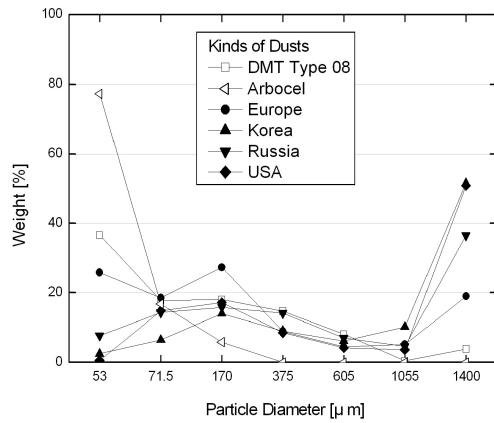
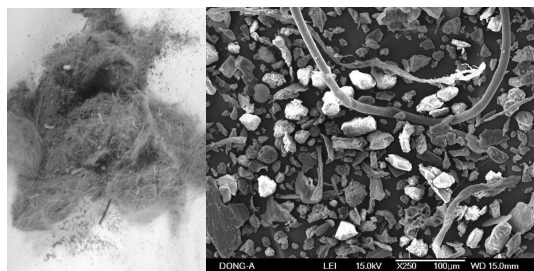
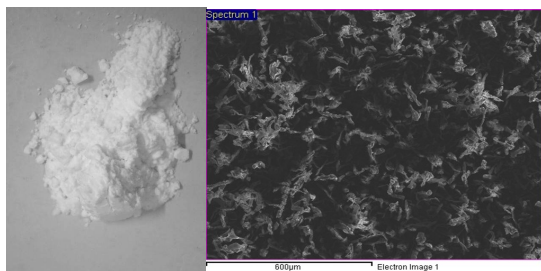


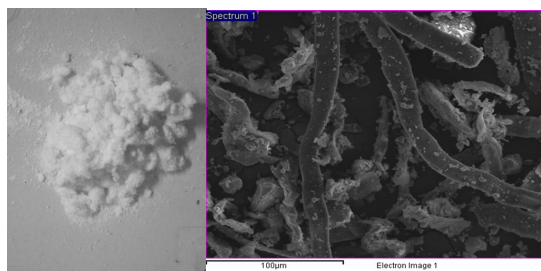
Fig. 1. Particle size distributions of various dust.



(a) House dust



(b) Arbolcel



(c) DMT type 08

Fig. 2. SEM pictures of the house dust, the arbolcel and the DMT type 08.

dust but also large debris such as tissue, papers, fur and hairs in house dust. In case of the twin cyclone, the friction force on plate is reduced to remove a bottom plate. So the dust outlet velocity of the twin cyclone is faster than conventional single cyclones. Therefore the twin cyclone shoots the large debris downwards into dust bin more easily than conventional single

cyclones. The new cyclone system sustains high level of suction power for a longer period.

2. Analysis of house dust

House dust is collected in several house buildings in Europe, Korea, Russia and USA. The collection of the house dust follows a standardized procedure. Each building is vacuumed twice a week during 4 weeks through normal house cleaning procedures. The physical compositions of the house dust, the arbolcel and the DMT test dust type 08 are analyzed. The arbolcel is a typical test dust used in evaluating the performance of vacuum cleaner and the DMT dust is a new type of test dust.

A sieve shaker is used to analyze the size distribution of the dust. The sizes of the sieve meshes are 53 μm , 90 μm , 250 μm , 500 μm , 710 μm , and 1,400 μm . The shaker is operated during 120sec. and the weight of each dust on the sieve is recorded. Fig. 1 shows the size distribution of each house dust and it is different from that of atmospheric aerosols. The most of arbolcel are smaller than 250 μm . However house dust consists of not only fine particles but also large size materials. Especially the dust from Korea and USA contains large particles over 1,400 μm .

Fig. 2 shows macro and micro images of house dust from Korea, arbolcel and DMT dust. The house dust and the DMT dust are composed of particles and fibers simultaneously; however, there are only fine particles in case of arbolcel. So the DMT dust is more proper for performance evaluation of vacuum cleaner instead of arbolcel.

3. Experiments

3.1 Design of cyclones and experimental set-up

Two single cyclones with central-hopper-dust-outlet (model A) and side-wall-dust-outlet (model B) and a twin cyclone (model C) were designed and fabricated for this study as shown in Fig. 3. Both models A and B have the different outlet type, but all other dimensions are same. Model C, the twin cyclone, has two inlets, two gas exits and one dust outlet, but the total area of inlets and gas exits are same compared with model A and B. The characteristic of the twin cyclone is that there is no plate between two cyclones. Dust-laden air enters tangentially into two inlets. Centrifugal force and inertia force separate the dirt and particle from dust-laden air. The dirt and particle move into a dust container connected to a dust outlet. The cleaned air exits from two gas exits.

Fig. 4 shows a schematic diagram of the experimental set-up. The standard dust and the actual residential dust are introduced into the inlet pipe through a dust feeder and collected in the cyclone. The pressure drop of the cyclone is measured using a manometer and the air flow rate is changed by control the suction motor speed. The suction air flow rate of vacuum cleaner for residential use is normally in the range of 1.0-1.8 m³/min and it is much larger than 30 m/s of inlet velocity. It is a considerably high flow rate compared with general industrial

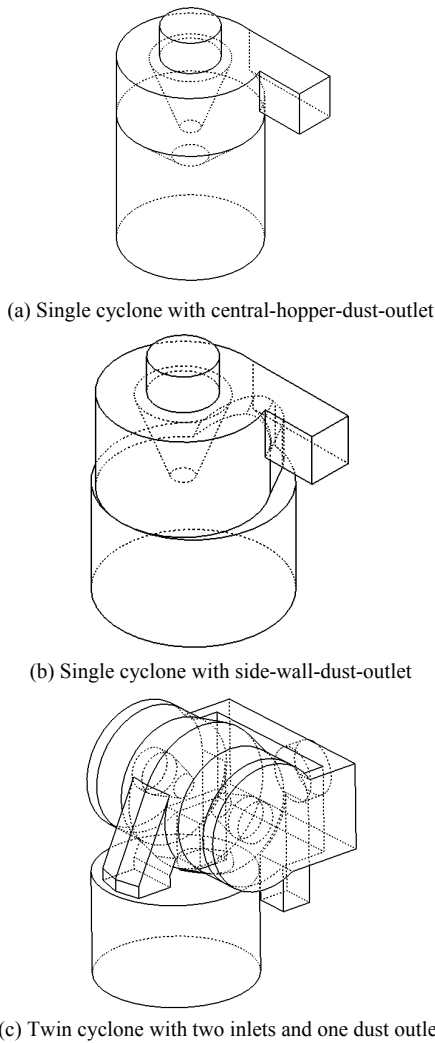


Fig. 3. Geometry of cyclones (a) single cyclone with central-hopper-dust-outlet; (b) single cyclone with side-wall-dust-outlet; (c) twin cyclone with two inlet and one dust outlet.

cyclone collectors.

3.2 Test dust and procedure

The performance evaluations of the cyclones are carried out by two methods. First method is the measurement of the dust collection efficiency by weight using DMT test dust type 08.

Secondly, the dust collection tests are carried out using the house dust which is taken from vacuum cleaners that had been used in real house situation. There are large size materials such as debris, hair, tissue paper and fluff.

3.2.1 The standard dust of DMT type 08

The test dust called DMT type 08 is composed of mineral dust, arbolcel and lint. The mineral dust is crystalline calcium magnesium carbonate (Dolomite, $\text{CaMg}(\text{CO}_3)_2$), and the ingredients of mineral dust are CaO 30.8%, MgO 21.6%, SiO_2 0.2%, $\text{Al}_2\text{O}_3 < 0.1\%$, $\text{Fe}_2\text{O}_3 < 0.02\%$, $\text{TiO}_2 < 0.01\%$, $\text{Na}_2\text{O} < 0.01\%$, $\text{K}_2\text{O} < 0.01\%$ and ignition loss 47.3%. The arbolcel is composed

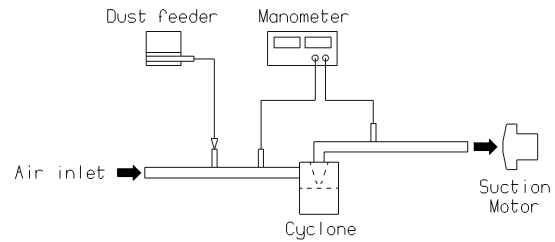


Fig. 4. Schematic diagram of experimental set-up.

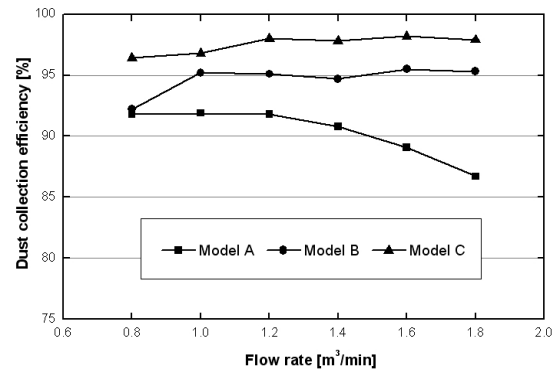


Fig. 5. Dust collection efficiency of cyclones with DMT type 08.

of 99.5% of particulate cellulose with the length of $30 \mu\text{m}$. The ingredients of lint are cut cotton fibers, and the fiber length is shorter than 4mm.

The total weight of dust container is measured before test. 100 grams of dust is introduced to the cyclone inlet. After all of 100 grams of dust has been sucked, the dust container is reweighed. The weight of dust in container is calculated from difference between the initial and final weight of the dust container.

The separation efficiency (η) is expressed by

$$\eta = \frac{W_{bin}}{W_{in}} = \frac{W_{final} - W_{initial}}{W_{in}} \quad (1)$$

W_{bin} : The weight of dust collected in dust bin

W_{in} : The weight of sucked dust

W_{final} : The weight of dust container after suction of dust

$W_{initial}$: The weight of dust container before suction of dust

3.2.2 The house dust

All the test work is carried out under the ambient temperature of $23 \pm 2 \text{ }^\circ\text{C}$, and relative humidity of $55 \pm 5 \%$. Prior to the initial test, the motor is kept running with unrestricted air flow for at least 2 hours to ensure adequate running-in. The dust used in these tests is taken from vacuum cleaners that have been used in an actual residential house. The test dust is prepared by screening to remove any particles larger than 20mm, and then sieved to separate the fine particles from the fluff. The fines and the fluff are homogenized and stored separately.

The fines and fluff are re-combined in their original propor-

Table 1. The dimensions of the twin cyclone.

Geometry	Dimension [mm]
Body diameter [mm]	ø100, ø110, ø120
Inner cylinder diameter [mm]	0.24D, 0.27D, 0.32D
Inner cylinder length [mm]	0.23D, 0.34D, 0.45D
Inlet size (height × width) [mm ²]	0.27D × 0.23D, 0.27D × 0.19D, 0.27D × 0.15D, 0.23D × 0.23D
Dust outlet size (height × width) [mm ²]	0.46D × 0.24D, 0.36D × 0.24D, 0.46D × 0.19D, 0.36D × 0.19D

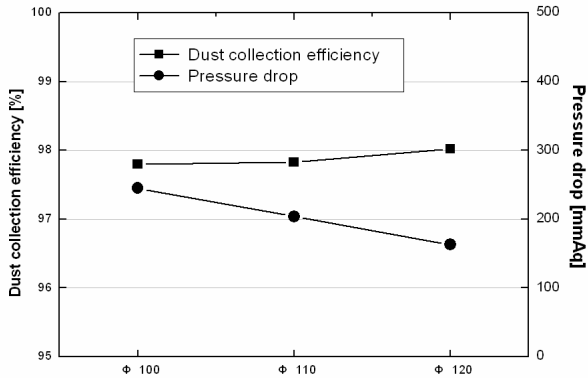


Fig. 6. The pressure drop and the dust collection efficiency of twin cyclone for various body diameters.

tions for each individual test.

The weight of the dust container is measured before test. 20 grams of dust is spread as evenly as possible over a flat board. The hose connected to cyclone inlet is moved across the dust-coated board at a speed that allows dust to be picked up at a rate of 2 grams per minute, until all the dust has been removed. This process is repeated with another 4 times of 20 grams so the cleaner has picked up 100 grams of dust in total. The dust containers are reweighed and the dust collection efficiency is calculated. The whole process is repeated three times and the results are averaged.

4. Results and discussion

4.1 Performance tests of the 3 cyclone models

Fig. 5 compares the dust collection efficiencies of 3 models of cyclones using the DMT test dust type 08. The model B and the model C show slightly increased separation efficiency according to the increase of air flow rate, however, the model A shows reversed result. The separation efficiency of the model C, the twin cyclone, is greater by 3–6% than those of two single cyclones. It was expected that dust would easily exit to dust bin because there is no bottom plate in the twin cyclone. On the other hand, there were bottom plates in two single cyclones, the centrifugal force on plate would be zero because of the friction with plate.

The pressure drops of the cyclones are 180.1, 178.4, and

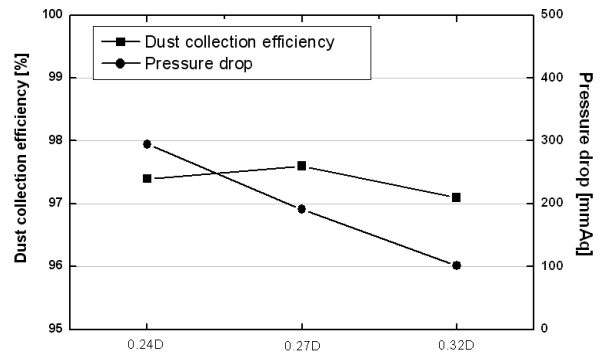


Fig. 7. The pressure drop and the dust collection efficiency of twin cyclone for various inner cylinder diameters.

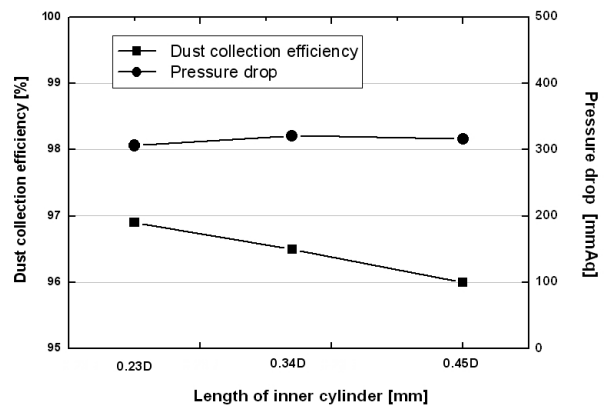


Fig. 8. The pressure drop and the dust collection efficiency of twin cyclone for various inner cylinder lengths.

203.9 mmAq, respectively for model A, B, and C at the flow rate of 1.8 m³/min. The dust collection efficiencies of the 3 models using the house dust collected in Korea are 90.2%, 96.0%, and 98.5%, respectively for model A, B, and C. The separation efficiency of twin cyclone is better by 2–8% points than those of two single cyclones. And the inside the cylinder of the twin cyclone is very clean after test. But the inside the cylinders of the two single cyclones are clogged by large dirt such as debris and hair. These clogging cause to increase the pressure drop of cyclone. Therefore the twin cyclone is selected as an adequate model to analyze for its high efficiency.

4.2 The optimization of twin cyclone

The separation efficiencies of the twin cyclone are evaluated at various body diameters, inner cylinder diameters, inner cylinder lengths, inlet sizes and dust exit sizes to optimize the twin cyclone performance more clearly. Table 1 shows the dimensions of the twin cyclone and all the dimensions except the body diameter are based on the body diameter of ø 110.

Fig. 6 shows the performances of the twin cyclone at the 3 sizes of the body diameter. As increasing the body diameter, the separation efficiency is increased and the pressure drop is decreased. They are very important factors of high efficiency and low pressure drop especially for a vacuum cleaner.

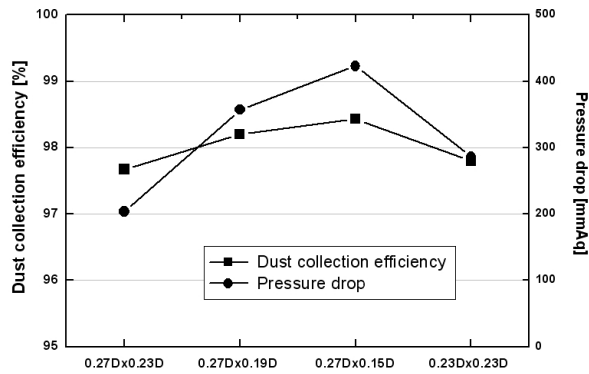


Fig. 9. The pressure drop and the dust collection efficiency of twin cyclone for various dust inlet dimensions.

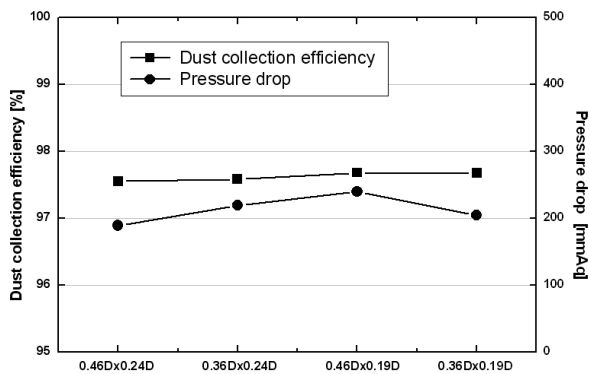


Fig. 10. The pressure drop and the dust collection efficiency of twin cyclone for various dust outlet dimensions.

However it also needs compactness to handle in case of canister type vacuum cleaner. So the case of $\phi 110$ is selected as a representative size. Fig. 7 and Fig. 8 show the effects of the dimensions of inner cylinder such as diameter and length. As the inner cylinder diameter is increased, the pressure drop is decreased abruptly. At the case of $0.32D$ in diameter shows very low pressure drop but some hairs, lint and long fibers twisted around the inner cylinder. Therefore considering the dust collection efficiency and the pressure drop, the case of $0.27D$ in diameter is more effective than $0.24D$ and $0.32D$. As the inner cylinder length is increased, all the values of the pressure drop are almost the same, and the dust collection efficiency is decreased. The case of $0.23D$ in length is clearly recommended as a best case.

Fig. 9 shows the cyclone performances according to the various inlet dimensions. The maximum pressure drop and dust collection efficiency are shown in the case of smallest inlet size of $0.27D \times 0.15D$. The small inlet makes high speed air velocity, and the centrifugal force which is a key factor to collect dusts in a cyclone system and the pressure drop are proportional to the air velocity. As the inlet velocity is increased, its dust collection efficiency is increased [8].

The pressure drop and the dust collection efficiency are different even the inlet areas of $0.27D \times 0.19D$ and $0.23D \times 0.23D$ are similar, so the inlet dimension is more important than inlet

Table 2. Optimal dimensions of the twin cyclone.

Geometry	Dimension [mm]
Body diameter, D [mm]	$\phi 110$
Inner cylinder diameter [mm]	$0.27D$
Inner cylinder length [mm]	$0.23D$
Inlet size (height \times width) [mm ²]	$0.27D \times 0.19D$
Dust outlet size (height \times width) [mm ²]	$0.36D \times 0.24D$

area in the rectangular inlet. The best dimension of inlet is $0.27D \times 0.19D$. Fig. 10 represents the cyclone performances according to the outlet dimensions. Dust collection efficiencies are almost the same and the pressure drops also show very close single value. The dust outlet dimension is selected as $0.36D \times 0.24D$ with the consideration of separation and rebound of large debris such as hair, paper, fur etc.

From the experimental results using the DMT test dust type 08 which is very close to Korean house dust, the optimal dimensions of the twin cyclone for canister type vacuum cleaner are summarized in Table 2.

5. Conclusions

In this study, house dusts collected from several foreign countries are investigated and compared standard dusts and designed 3 types of cyclones. Among the cyclones, a twin cyclone, with two inlets and one dust outlet, is designed, and evaluated to derive an optimal image. The summarized conclusions are below.

- (1) The DMT test dust type 08 is similar to the house dust and the arbocel is not adequate to represent the house dust.
- (2) The dust collection efficiency of twin cyclone is greater, by 3-6%, than those of two single cyclones using DMT test dust.
- (3) The separation efficiency of house dust is similar to that of DMT test dust. And the inner cylinder of twin cyclone is very clean even after several experiments, compared with two single cyclones.
- (4) Twin cyclone with a large body diameter, a small inner cylinder diameter, a short inner cylinder, a narrow inlet has high separation efficiency, and optimal dimensions for canister type vacuum cleaner are derived.

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