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Numerical Analysis of Axial-Flow Cyclone Separator for Subway Station HVAC System Pre-Filter

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Abstract

In the Korean subway station, three types of pre-filters, which include auto filter, electrostatic precipitator (ESP) and auto cleaning demister, are widely used. However, these devices have some problems such as the difficulty of maintenance and high operating cost. In this study, axial-flow cyclone separator was employed as a pre-filter inside a heating, ventilation, and air conditioning (HVAC) system. 3-dimensional computational fluid dynamics (CFD) analysis was performed on a single unit axial-flow cyclone and coupled unit axial-flow cyclone. Calculated and measured pressure drop of the designed axial-flow cyclone were found be comparable to other types of pre-filters and the observed cut-off diameter was less than 10 micron. Considering lower operating and maintenance cost, axial-flow cyclone was proved to be a better solution as a pre-filter.

Key words: Axial-flow cyclone, CFD, Pre-filter, Subway HVAC

Nomenclature

Re : Reynolds number
u : flow velocity [m/s]
u_p : particle velocity [m/s]
D_p : diameter of particle [m]
μ : viscosity [N · S/m^2]
ρ : density [kg/m^3]
k : turbulence kinetic energy
ω : turbulent kinetic energy dissipation rate
r_{max} : inside radius of cyclone [m]
r_{min} : radius of vane spindle [m]
N : number of vanes
n : number of vane turns
P : pitch of vane [m]
t : thickness of vane [m]
D_{in} : diameter of verification model inlet [m]
D_{out} : diameter of verification model outlet [m]
L_{di} : length of diffuser [m]
L_{no} : length of nozzle [m]
d_{out} : diameter of cyclone outlet [m]

Subscript

p : particle

1. Introduction

The Korean subway system has continuously grown since metropolitan subway started its service in 1974. Now, it covers Seoul metro area and other big cities including Busan, Daegu, Gwangju and Daejon, and its share in the total transportation has been dramatically increased. According to the statistics compiled from Seoul metropolitan government, the number of daily metropolitan subway system users are about 7.2 million in 2007, and it is still increasing.(1) As subway system has become a part of the daily life, its indoor air quality draws the attention of the public. As most subway stations use underground

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space where ventilation is difficult, its air quality has inherent problem. Especially, there are many dust sources such as metal particles from friction of train wheel, blown-up dust by train wind and incoming outside particles.(2) As a result, the level of particulate matter in the subway station is relatively high. Many researches have been performed to measure the concentration of particulate matter generated by public transportation and the concentration was higher than the IAQ standard.(3-5) Korean subway system is not an exception.(6) According to the study of Karlsson et al, subway particles are roughly eight times more genotoxic and can cause oxidative stress four times more in lung cells than street particles(7). Thus the control of particle concentration in subway system is very important.

In the Korean subway station HVAC system, three types of pre-filters; auto filter, electrostatic precipitator (ESP) and auto cleaning demister, are typically used. The performance of these filters deteriorates with the increase of operating hours. If dirty air passes through the filter, a cloud of dust is formed and blocks the air path ways. While particle removal efficiency increases, pressure loss gets higher. Eventually, cleaning method such as air suction or high-pressure water jet is necessary, but it is time-consuming and causes high maintenance cost.

Recently Kwon et al. suggested new type of axial-flow cyclone separator as a pre-filter which can overcome these drawbacks of conventional pre-filters.(8)

The cyclone separator is one of the most widely used separation device in the industry. Advantages, such as the constant pressure drop, high throughput with moderate efficiencies, have made the cyclone the most attractive solution as a pre-filter in the dust removal device.(9) Cyclone uses the centrifugal force for removing particles from the main flow. If the direction of the main flow is rapidly changed, particles cannot follow the main stream due to the relatively high inertial force.

Cyclone separator is classified mainly into two types according to its main stream direction. One is the tangential-flow cyclone separator and the other is the axial-flow cyclone separator. The former device is conventionally used cyclone which change main stream direction by 90 degn bs. Sudden change can result in the high particle removal efficiency, but volume of the device is large with high pressure drop. Because the ch chanstreaunit has limited space and pump capacity, it is not chcleble.nsowever, axial-flow cyclone separator using fixed blades to induce high centrifugal force does not change the direction of the main stream Thus, the axial-flow cyclone is appropriate for ch chanstreapre-filter because it has small volume and low pressure drop. Fig. 1 is an axial-flow cyclone pre-filter. It consists of several axial-flow cyclones.

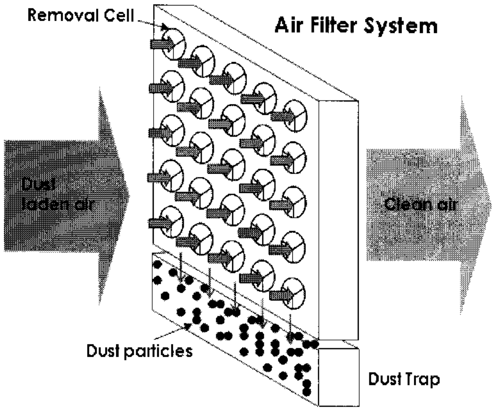


Fig. 1. Schematic of air filter system containing many axial-flow cyclones.

In this study, the single unit axial-flow cyclone and the coupled unit axial-flow cyclone were evaluated as a pre-filter for subway station HVAC system using CFD analysis with commercially available, FLUENT.

2. Numerical analysis

2.1 Transport equations

With the inlet flow velocity of 2.5m/s, the flow in the axial-flow cyclone is in the turbulent regime, because Reynolds number is between 7500 and 20000. Thus, shear-stress transport (SST) *k-ω* model, which is one of the widely-used turbulence models, was used. SST *k-ω* model was developed by Menter to effectively blend the robust and accurate formulation of the k-ω model in the near-wall region with the free-stream independence of the *k-e* model in the far field. To achieve this, the *k-e* model is converted into a *k-ω* formulation. The SST *k-ω* model is similar to the standard k-e model, but SST *k-ω* model is more accurate and reliable for a wider class of flows than the standard *k*-e model.

Transportation equation which includes *k* and *ω* is shown as below in Eqs. (1) and (2).

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)= \tag{1}$$

$$\frac{\partial}{\partial x_j}\left[(\Gamma_k)\frac{\partial k}{\partial x_j}\right]+\tilde{G}_k-Y_k \tag{1}$$

and,

$$\frac{\partial}{\partial t}(\rho\omega)+\frac{\partial}{\partial x_i}(\rho\omega u_i)= \frac{\partial}{\partial x_j}\left[(\Gamma_\omega)\frac{\partial \omega}{\partial x_j}\right]+G_w-Y_w+D_w \tag{2}$$

where $\tilde{G}_k$ represents the generation of turbulence kinetic energy due to mean velocity gradients. G_ω represents the generation of ω. Γ_k and Γ_ω represent the effective diffusivity of k and ω, respectively, which are calculated as described below as given in Eqs. (3) and (4).

$$\Gamma_k=\mu+\frac{\mu_t}{\sigma_k} \tag{3}$$

and,

$$\Gamma_\omega=\mu+\frac{\mu_t}{\sigma_\omega} \tag{4}$$

where σ_k and σ_ω are the turbulent Prandtl numbers for k and ω, and μ_t is turbulent viscosity.

Y_k and Y_ω represent the dissipation of k and ω due to turbulence, which are defined in Eqs. (5) and (6).

$$Y_k=\rho\beta^* k\omega \tag{5}$$

and,

$$Y_\omega=\rho\beta\omega^2 \tag{6}$$

D_ω represents the cross-diffusion term.

2.2 Equation of particle motion

Lagrangian description was used for the analysis of particle motion. It predicts the trajectory of a discrete phase particle by integrating the force balance on the particle inertia with the forces acting on the particle, and can be written as given in Eq. (7).

$$\frac{du_p}{dt}=F_D(u-u_p)+\frac{g_x(\rho_p-\rho)}{\rho_p} \tag{7}$$

where first term is the drag force per unit particle mass and second term is gravitational force term. F_D can be obtained using Eq. (8) from Stokes' drag law.

$$F_D=\frac{18\mu}{d_p^2\rho_p C_c} \tag{8}$$

The factor C_c is the Cunningham correction, which we can be computed from Eq. (9).

$$C_c=1+\frac{2\lambda}{d_p}(1.257+0.4e^{(-1.1d_p/2\lambda)}) \tag{9}$$

where λ is the molecular mean free path.

The integration time step(Δt) is computed by FLUENT based on a specified length scale *L*, and the velocity of the particle(u_p) and of the continuous phase (u_c)

$$\Delta t=\frac{L}{u_p+u_c} \tag{10}$$

In this study, adequate *L* which did not influence particle tracking result was used for discrete phase model.

3. Results and discussion

3.1 Modeling

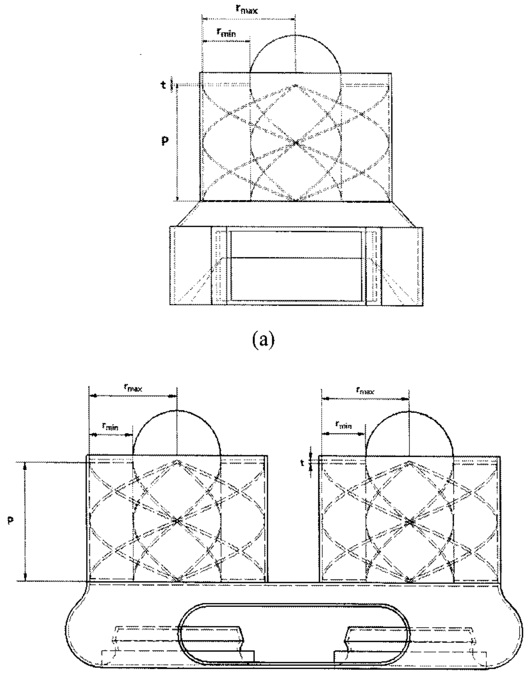
As the first step, single unit axial-flow cyclone and the coupled unit axial-flow cyclone were analyzed before analyzing full-scale model, which is the subject of future research. Model of each unit is shown in the Fig. 2. and dimensions of each unit are listed in the Table 1. A long cylinder at the bottom of each unit, is used as the dust trap for the collection of precipitated particles.

Single unit is modeled with 1 million tetrahedral mesh, and coupled unit is modeled with 3 million tetrahedral mesh using GAMBIT which is a grid generation program of FLUENT software. The mesh number distinction is due to the size of each unit. Inlet condition was set to flow velocity of 2.5 m/s. Outlet condition was set to atmospheric pressure.

Particles were assumed to have density of water and diameter in the range of 2 micron to 15 micron. About 4000 particles for each diameter were uniformly distributed on the cross sectional area of the inlet initially. Particles were assumed to be removed if they are impacted or intercepted on the wall.

Table 1. Dimensions of the single unit and coupled unit axial-flow cyclone.

	Single unit	Coupled unit
r_{max} (mm)	60	60
r_{min} (mm)	30.65	30
P (mm)	75	80
t (mm)	1	2
N	4	4
n	0.5	0.5



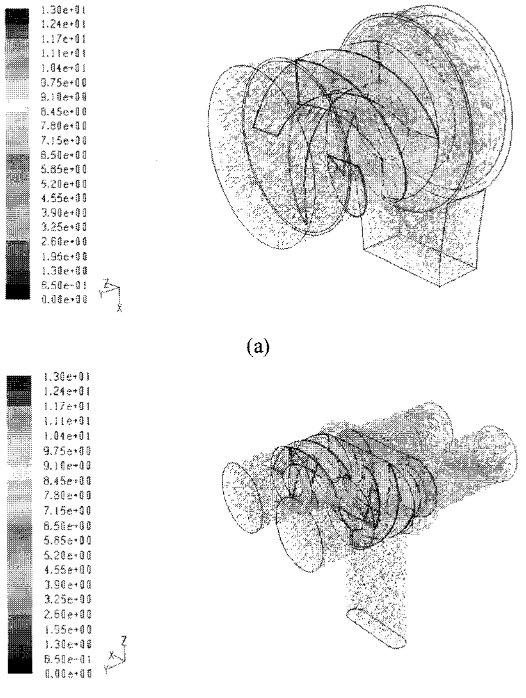
(b)

Fig. 2. Schematics of analysis models used for evaluation. (a) single unit, (b) multi unit axial-flow cyclone.

Also we assumed that numerical calculation is done when the residual of velocity, continuity, k and ω were below 10^{-4}.

3.2 Simulation results

As discussed in the introduction, axial-flow cyclone uses centrifugal force to remove particles. Flow velocity is important because it is related to both centrifugal force and pressure drop. Fig. 3 is the velocity vector field. At the inlet, velocity magnitude was 2.5 m/s, but after flow passed through the blade, velocity magnitude was increased to over 10 m/s. It means that the most pressure drop occurred within the blades and that the most removed particles were trapped or intercepted by the blade surface.



(b)

Fig. 3. Velocity vector of analysis models (a) single unit, (b) multi unit axial-flow cyclone.

Simulation results showed that the pressure drop of the single unit axial-flow cyclone was 11.08 mmH_2O, and the coupled unit axial-flow cyclone was 9.53 mmH_2O, which indicates that the axial-flow cyclone has similar levels of pressure drop compare to other pre-filters. Especially, it is worth while to know that the single unit and the coupled unit have similar pressure drop. Presumably, this shows that the total pressure drop of axial-flow cyclone filter is mostly influenced by the pressure drop of each single cyclone unit.

The major role of pre-filter is removing large particles (tens of microns) to reduce dust load at the after-stage filters. Particle removal efficiency of present pre-filters are presently evaluated by weighting method. However, with the reduction of contaminant particle size, counting method can provide more meaningful data. Thus, the counting method is used in this study. Considering performance of other types of pre-filters, 10 micron was set to be a target cut-off diameter.

Table 2 shows the calculated particle removal efficiency. According to the simulation result, single unit has about 9 micron cut-off diameter, and coupled unit has about 10 micron cut-off diameter. These results

Table 2. Particle removal efficiency for the single unit and coupled unit axial-flow cyclone.

$D_p (\mu m)$	Single unit(%)	Coupled unit(%)
2	16.12	10.90
5	21.09	15.97
8	38.10	36.95
10	60.03	51.27
12	82.90	67.05
15	94.18	82.11

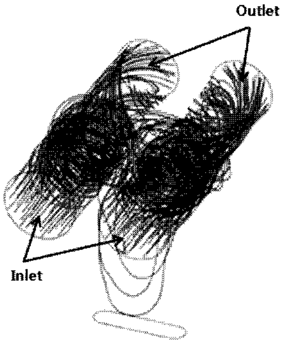


Fig. 4. Air flow stream line in coupled unit axial-flow cyclone evaluated using SST k-ω model.

satisfy the design objective. Moreover if real-world particles, which are typically heavier than water droplets, are used, particle removal efficiency can be increased because denser particles have higher inertial force.

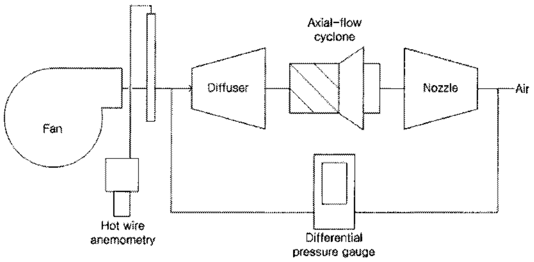
In Fig. 4, streamline interference is found in the coupled unit, which is not found in the single unit. Red line indicates the streamlines starting from right side inlet and blue line indicates stream lines starting from left side inlet. Almost all the stream lines exit through the same direction of the outlet, while some stream lines crossed to the other side of the outlet. Coupled unit with blocking structure in connection point was also evaluated. There are no special differences with the former case. It seems that the effect of stream line interference to the performance of the cyclone is insignificant. However, this phenomenon can be a potential risk if the cluster consists of more than 3 units. So it should be considered in the future study.

3.3 Verification of simulation model

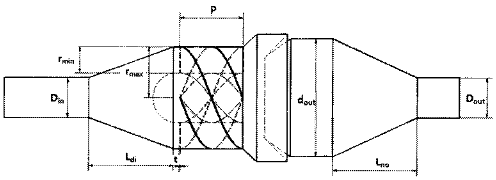
To validate CFD results, we compare the result of experimental pressure drop measurement with that of computational calculation. Fig. 5(a) shows the experimental setup, which consists of mock-up axial-flow cyclone, fan and connecting pipes. Diffuser and nozzle were used, because diameter of pipes and axial-flow cyclone were different. Flow velocity was measured in front of the nozzle. Pressure drop measurement was carried out by measuring pressure difference between the points upstream of diffuser and downstream of nozzle. Fig. 5(b) is a simplified model of experiment setup, and its dimensions are listed in the Table 3.

Table 3. Dimensions of verification model dimensioned in Fig. 4.

Parameter	Numerical model
r_{max} (mm)	60
r_{min} (mm)	30.65
P (mm)	75
t (mm)	1
D_{in} (mm)	47
D_{out} (mm)	47
d_{out} (mm)	138.85
L_{di} (mm)	100
L_{no} (mm)	100
N	4
n	0.5



(a) Schematic of experimental setup



(b) Numerical model

Fig. 5. Pressure drop measurement setup and its corresponding numerical model for verification.

We measured the variation of pressure drop by changing inlet flow velocity from 3 m/s to 20 m/s. The experimental and numerical analysis results are compared in the Fig. 6. Experimental data are marked as a point with error bar and numerical results are shown as a line. The difference between experimental and numerical analysis was less than 4%.

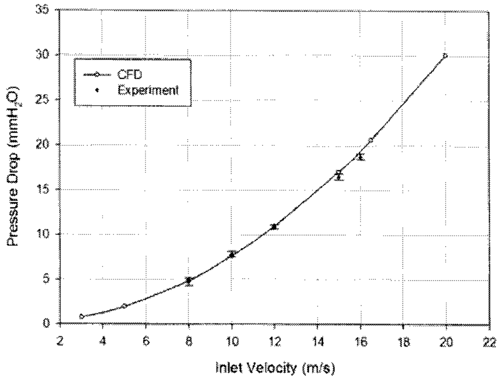


Fig. 6. Comparison of numerical pressure drop calculation result with experimental measurement result.

4. Conclusions

In this study, we evaluated the axial-flow cyclone which is used as a pre-filter of subway HVAC system using numerical analysis. Simulation was performed on a single unit axial-flow cyclone and a coupled unit axial-flow cyclone. Cut-off diameter of axial-flow cyclone was smaller than 10 micron. It means the particle removal efficiency of axial-flow cyclone is acceptable as a pre-filter, and it can be improved more in the future study. Also, the pressure drop of the axial-flow cyclone was similar to other pre-filters. As the axial-flow cyclone has uniform pressure drop, regardless of operating time, it can reduce not only operating cost, but also maintenance cost. Simulation method was validated by comparing with the experimental measurement of pressure drop.

In conclusion, axial-flow cyclone was found to have good performance with the potential for lower operating and maintenance cost. Therefore it can be a more suitable pre-filter than other pre-filters to be used in the subway station HVAC system.

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