



Novel Air Filtration Device for Building Air Handling Unit

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ABSTRACT

Particulate matter (PM) is one of the major indoor air pollutants in the subway-underground stations in Korea. Various kinds of PM removal methods such as a roll-filter, auto-washable air filter, demister, and electrostatic precipitator are applied in the air handling unit (AHU) of subway station. However, those systems are faced with operation and maintenance problems since the filter-regeneration achieved by air or water jet is often malfunctioned due to the high load of particulates. The filter material also needs periodic replacement. In this study, we designed a novel particle removal system with minimized maintenance requirement compared to above mentioned filter systems. The new system named as panel-type cyclone system was suggested and the key part of the system was developed based on the axial-flow cyclone where the air flow pattern lies on the same axis with air stream through passing the AHU. The shape of axial-flow cyclone was optimized to remove 50% of 2.5 μm -sized particulate matters with minimal pressure drop by using the tool of computational fluid dynamics. We believe that the novel axial-flow cyclone system is cost-effective and efficient way of removing particulate matters in the size range of 1–10 μm in the AHU of subway station or buildings.

Keywords: Filtration; Axial-flow cyclone; Air handling unit (AHU); Particulate matter; Panel-type cyclone.

INTRODUCTION

Since the first Korean subway was opened in 1974, the subway network system has been expanded to cover Seoul metropolitan area and to other cities of Busan, Daegu, Daejeon, and Gwangju and their traffic share among public transportation has been increased significantly. According to statistics compiled from Korean ministry of land, transport and maritime affairs (MLTM), a number of daily nationwide subway system users are about 8.5 million in 2009, and it is still increasing. It means using subway system has become a part of our daily life nowadays. However, management of indoor air quality (IAQ) in subway system is not enough to follow its development (Adams *et al.*, 2001; Gomez-Perales *et al.*, 2004; Kwon *et al.*, 2008; Park and Ha, 2008). It is reported that Americans spend 87% of their daily time in indoor space, and 5% of their time in a transportation vehicles (Klepeis *et al.*, 2001). With increasing time in indoor space, i.e., building, transportation, etc., the management of IAQ becomes key issue for healthy life of modern people.

Particles smaller than 10 μm (PM₁₀) are small enough to reach lung cells, which can affect on human dust protection system (Heyder, 2004). Plenty of particles deposited in the lung cells can induce respiratory diseases. Small amount of particles can induce damage to lung cells if they have dangerous toxicity. According to the research of Karlsson *et al.* (2005), subway particles are generally eight times more genotoxic and cause oxidative stress four times more in lung cells than street particles.

For these reasons, it is very important to remove the airborne particles from the subway station. In air handling unit (AHU) of Korean subway station, a fabric air filter has been used widely as a dust removal device. A fabric filter has good efficiency and it satisfies the design requirements, such as collection efficiency, and pressure drop. However, it has many problems when a cloud of dust is formed and blocks air path ways. Thus, the pressure drop increased as dust particles block the filter. Therefore the most significant problem is short life time of a filter, which increases its replacement frequency. Frequent changing of filters induces high maintenance cost and effort.

Cyclone separators are 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. The former device changes the main stream direction to the 90° angle (tangential-flow type). A sudden change of the

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main stream can result high efficiency, but the volume of the device and the pressure drop are also high in this case. Because the subway AHU has limited space, tangential-flow cyclones are not suitable. However, the axial-flow cyclone does not change the direction of the main stream. It uses a vortex vane to induce high centrifugal force. The axial-flow cyclone is suitable for replacing the current filter system, because it has small volume and low pressure drop (Brunazzi *et al.*, 2003).

There are only few researches which studied the axial-flow cyclones compared to those on the tangential-flow cyclone. Weiss *et al.* (1987) developed axial-flow cyclones to provide clean air for Czechoslovakian miner. Wedding *et al.* (1982) developed the axial-flow cyclone as a pre-separator for removing particles smaller than 10 μm . It was one of the earliest application of axial-flow cyclone. Vaughan (1988) designed, constructed and tested a simple axial-flow cyclone which consists of helical channel, cylindrical body and exit tube. He concluded the axial-flow cyclone had smaller cut off diameter than tangential cyclones of similar device size. Nieuwstadt *et al.* (1995) reported a fluid-mechanics model for the axial-flow cyclone, and Maynard (2000) studied the performance of axial-flow cyclone under laminar flow condition theoretically. Hsu *et al.* (2005) argued that the axial-flow cyclone can collect ultrafine particles, and Tsai *et al.* (2004) performed a research on the axial-flow cyclone operated in vacuum condition. Recently Hsiao *et al.* (2010) developed multi-stage axial-flow cyclones consisting of the impaction inlet and fine axial-flow cyclones. They also developed the axial-flow cyclone for separating nanoparticles of 272–448 nm (Hsiao *et al.*, 2011).

In this study, we suggested a novel concept of a panel-type cyclone system, designed the axial-flow cyclone, and evaluated it using computational fluid dynamics (CFD) method with experimental evaluation. The novel axial-flow cyclone system was analysed in terms of particle collection efficiency and pressure drop.

METHODS

Concept of Panel-type Cyclone System

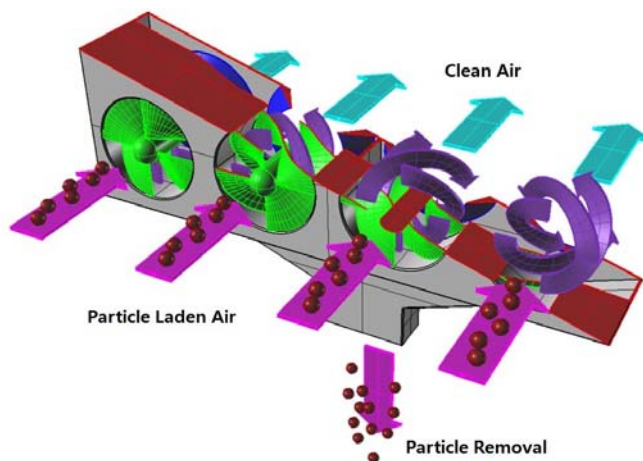
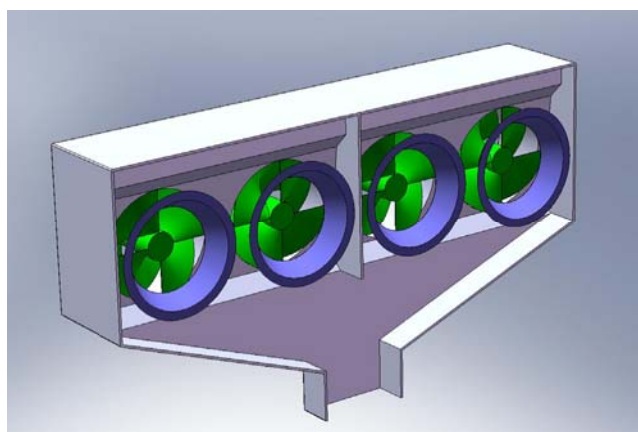


Fig. 1. Concept of axial-flow cyclone panel for AHU.

A cyclone separator is widely used for dust or droplet removing from the main flow. This device has some advantages such as, constant pressure drop, high throughput with moderate efficiency and low maintenance cost (Slack *et al.*, 2000). In this study, we focused on the replacement of the current air filter system in the AHU of a subway station. Especially, the target system was chosen as an AHU of subway station where major source of particles are in coarse mode particle size. The problem of current system is the fast blocking of dust on the fabric filter medium causing high pressure drop due to relatively large particle size and high particle load. A novel axial-flow cyclone was suggested in order to enhance particle collection efficiency while minimizing operating cost, which could replace the existing filter type particle collector in an AHU. The novel cyclone system consists of a pair of axial-flow cyclones where the particle vortex flow is generated in the opposite direction and a dust tray for collecting removed particles. Aerosol particles larger than the cut-off diameter are deviated from the air flow and thus they dropped vertically to the dust tray. Fig. 1 shows the concept of two pairs of axial-flow cyclone where the particle laden air is passing the vortex vane and exiting on the same axis. Particles were deviated from the flow path during the circulation of main flow due to a centrifugal force. The system utilizes the flow generated by the fan of the AHU and therefore the vortex vane is static on the body.

Transport Equation of Computational Fluid Dynamics (CFD) Analysis

We can define turbulence flow in the axial-flow cyclone by calculating Reynolds number in a condition of inlet flow velocity is 2.5 m/s and 5 m/s. In previous our research which compares numerical results with experimental results using the mock-up axial-flow cyclone, the shear-stress transport (SST) $k-\omega$ model shows better result than the standard $k-\epsilon$ model (Kim *et al.* 2009). So, we used the SST $k-\omega$ model. The SST $k-\omega$ model was developed by Menter (1994), and it gives highly accurate predictions of the onset and the amount of flow separation under adverse pressure gradients. The continuity equation, the momentum equation and the

transportation equation about k and ω are shown below. We assumed the flow is in incompressible and steady state condition.

$$\rho \frac{\partial}{\partial x_j} (u_i) = 0, \quad (1)$$

$$\rho \frac{\partial}{\partial x_j} (u_i u_j) = -\frac{\partial}{\partial x_i} p + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right], \quad (2)$$

$$\rho \frac{\partial}{\partial x_i} (k u_i) = \frac{\partial}{\partial x_j} \left[\Gamma_k \frac{\partial k}{\partial x_j} \right] + G_k - Y_k, \quad (3)$$

$$\rho \frac{\partial}{\partial x_i} (\omega u_i) = \frac{\partial}{\partial x_j} \left[\Gamma_\omega \frac{\partial \omega}{\partial x_j} \right] + G_\omega - Y_\omega, \quad (4)$$

where G_k represents the generation of turbulence kinetic energy and G_ω represents the generation of ω . Γ_k and Γ_ω represent the effective diffusivity of k and ω . Y_k and Y_ω represent the dissipation of k and ω .

Particle Motion Equation of CFD Analysis

In this study, we used the Euler-Lagrangian method for the analysis of particle motion. This 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

$$\frac{du_p}{dt} = F_D (u - u_p) + \frac{g_x (\rho_p - \rho)}{\rho_p}, \quad (5)$$

where the first term is the drag force per unit particle mass and the second term is the gravitation force term. F_D can be written as

$$F_D = \frac{18\mu}{d_p^2 \rho_p C_c}. \quad (6)$$

The factor C_c is the Cunningham correction to the Stokes' drag law, which can be computed from

$$C_c = 1 + \frac{2\lambda}{d_p} \left(1.257 + 0.4e^{-\left(\frac{1.1d_p}{2\lambda}\right)} \right), \quad (7)$$

where λ is the molecular mean free path.

Analysis Model and Mesh

We analyzed a 3-D model of the vortex vanes and the axial-flow cyclone by using the commercial computational fluid dynamics program (CFX, Ansys Inc.) to simulate the inner flow and particle trajectory. Fig. 2 shows the one pair of cyclones and the shape of the surface mesh. The total number of mesh elements was 4.3 million, and the prism layer was used for boundary layer analysis. For the turbulent analysis, the SST model was used and a high resolution advection scheme (2nd order) was applied. Particles are supposed to attach to the wall. For particle trajectory analysis, a maximum tracking time of 100 s and a maximum tracking distance of 100 m were assumed. The inlet velocity of flow was set to 5 m/s and 2.5 m/s.

Experimental Setup

The collection efficiency of the cyclone was evaluated using the experimental setup as shown in Fig. 3. Test particles were generated from the solid particle generator (SAG 401, Topas Co.) at the inlet of wind tunnel (600 mm × 600 mm). The size range of solid particles (A1 dust; $\rho = 2650 \text{ kg/m}^3$) was 0.68–12.6 μm . The flow rate was adjusted to match with the face velocity of 2.5 m/s or 5.0 m/s at the cyclone inlet. The particle number concentration was monitored using a particle counter (Dust Spectrometer, Grimm Inc.) at the inlet (N_{in}) and the outlet (N_{out}) of the cyclone and the collection efficiency was calculated by the ratio of particle numbers, $(N_{\text{out}} - N_{\text{in}})/N_{\text{in}}$.

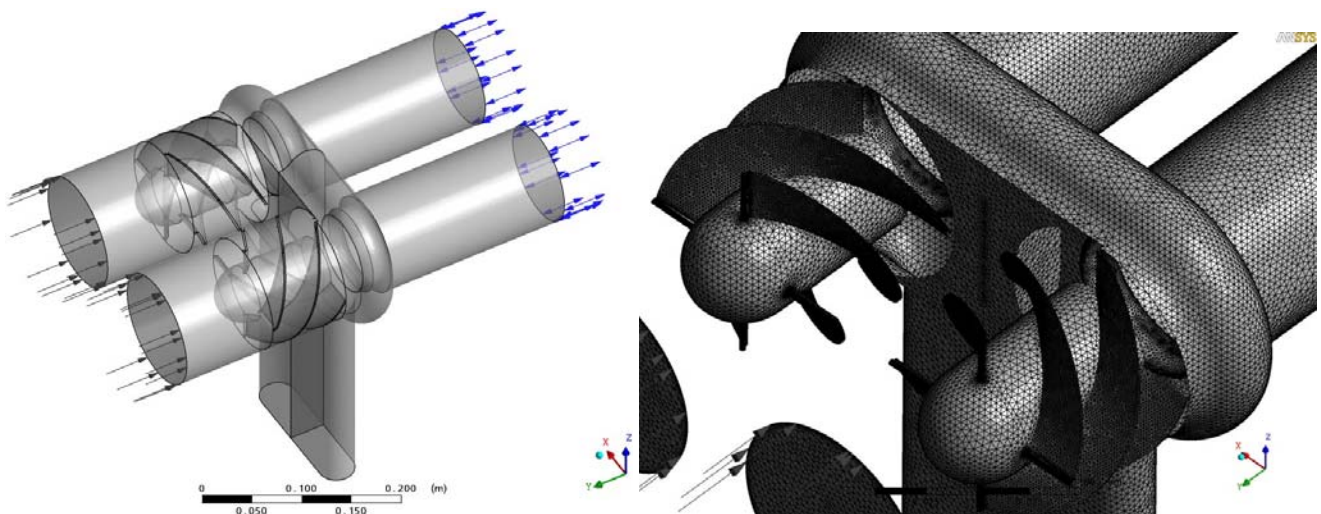


Fig. 2. Double axial-flow cyclones and its mesh element for numerical analysis.

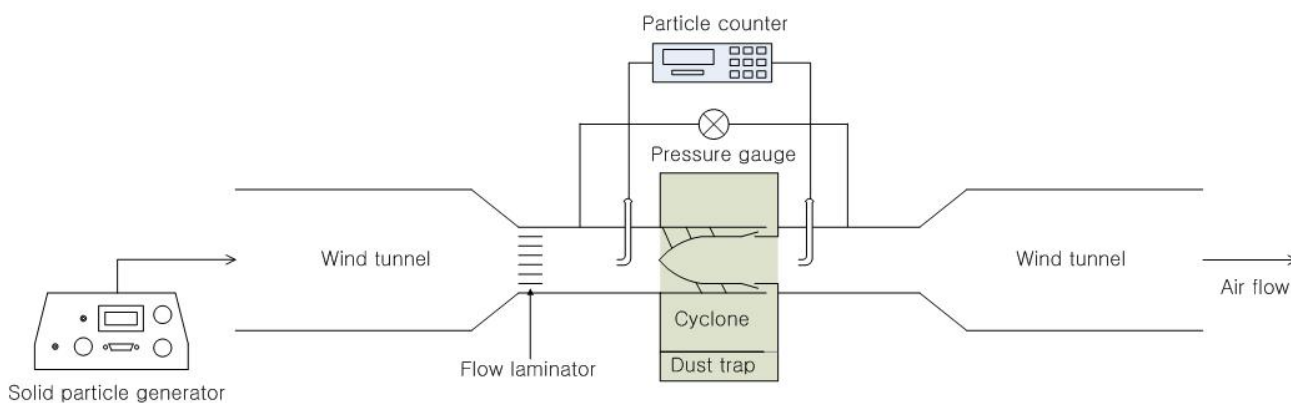


Fig. 3. Experimental setup for evaluating collection efficiency of axial-flow cyclone.

RESULTS AND DISCUSSION

Collection Efficiency

Fig. 4 shows the streamlines of two parallel cyclones and the surface-pressure distribution from the CFD calculation. It was found that the flow pattern in each axial-flow cyclone was not symmetric due to a slight difference in mesh structure as shown in Fig. 2. Therefore, the collection efficiency of each cyclone was different slightly. The pressure drop through the two cyclones was estimated as 327 Pa. From Fig. 4, it was found that the particles removed from one cyclone transported to another cyclone which could reduce the collection efficiency.

The collection efficiency of the cyclone was calculated by releasing 18,000 particles into the inlet of cyclone. We found a size dependent collection efficiency, and the two cyclones showed 3–13.5% difference in efficiency as shown in Table 1. As the particle size increased, the removal efficiency increased due to the increased inertia of particles. The average efficiency of 74.9% for particles of 1–10 μm was found. It should be noted that the target particle size range is 1–10 μm , with a higher than 50% removal efficiency at the particle size of 2.5 μm . Thus most of submicron particles (smaller than 1 μm) are supposed to penetrate the cyclone. The collection efficiency of experimental data was higher than numerical ones (2.5 m/s), however the increasing tendency was similar in numerical and experimental data. The deviation increased with particle size and the average deviation was approximately 30%. The reason for the higher collection efficiency of experimental data was regarded as the particle loss in the walls of wind tunnel by inertial deposition and interception. This particle loss needs further analysis in order to estimate the collection efficiency of cyclone itself.

Fig. 5 shows the particle trajectory of 1–4 μm sized particles and 7–10 μm sized particles respectively. After circulating around a vortex vane, 57.4% of particles are removed (depositing to the wall and downward to the dust trap) for 1–4 μm sized particles, however, about 91.5% of inlet particles were removed for over 7 μm sized particles. The pattern of particle trajectory is found to be slightly different in a cyclone pair, probably due to slight difference in the analyzing mesh geometry.

Effects of Inlet Velocity and Scale

A typical face velocity of the air filter in an AHU is 2.5 m/s in Korea. Our axial-flow cyclone system was designed with a face velocity of 2.5 m/s. However, it was found that the face velocity varies up to 5 m/s depending on the capacity of AHU. We calculated the collection efficiency when the inlet velocity of 2.5 m/s and 5 m/s in order to evaluate the feasibility for different sized AHUs. In addition, the scale-up model where the ratio of cyclone dimension remains constant was estimated to increase the applicability. Fig. 6 compares the collection efficiency of different inlet velocities. The collection efficiency of 2.5 m/s decreased by 37–53% compared to 5 m/s of inlet velocity. The case of scale-up (s-u) in Fig. 6 was compared also. The scale-up model had 2 times enlarged dimensions of the original model which could cover large filtering area with small number of cyclones when it is applied to the AHU. It was found that the collection efficiency of the scale-up model showed a more flat efficiency curve when compared to the original model at the face velocity of 2.5 m/s. A slightly higher collection efficiency was found for particles of smaller than about 6.5 μm , but the increase of efficiency is low compared to original size model over 6 μm .

SUGGESTIONS

For the practical application of the present axial-flow cyclone into the AHU of subway station, we suggest the cyclone-panel system as sketched in Fig. 7. The numbers of axial-flow cyclone units are arrayed, and a dust trap is installed under the cyclones, which collect the removed dust. The panel-type cyclone system can be fit to the inside of AHU housing.

CONCLUSIONS

We suggested the novel axial-flow cyclone system consists of two parallel cyclones for replacing the current air filter system in AHU of subway station. The concept was simulated with computational fluid dynamics, and the results showed a 75% of average collection efficiency for the particle size range between 1–10 μm with a static pressure drop of 327 Pa. The effect of decrease in inlet velocity on the collection

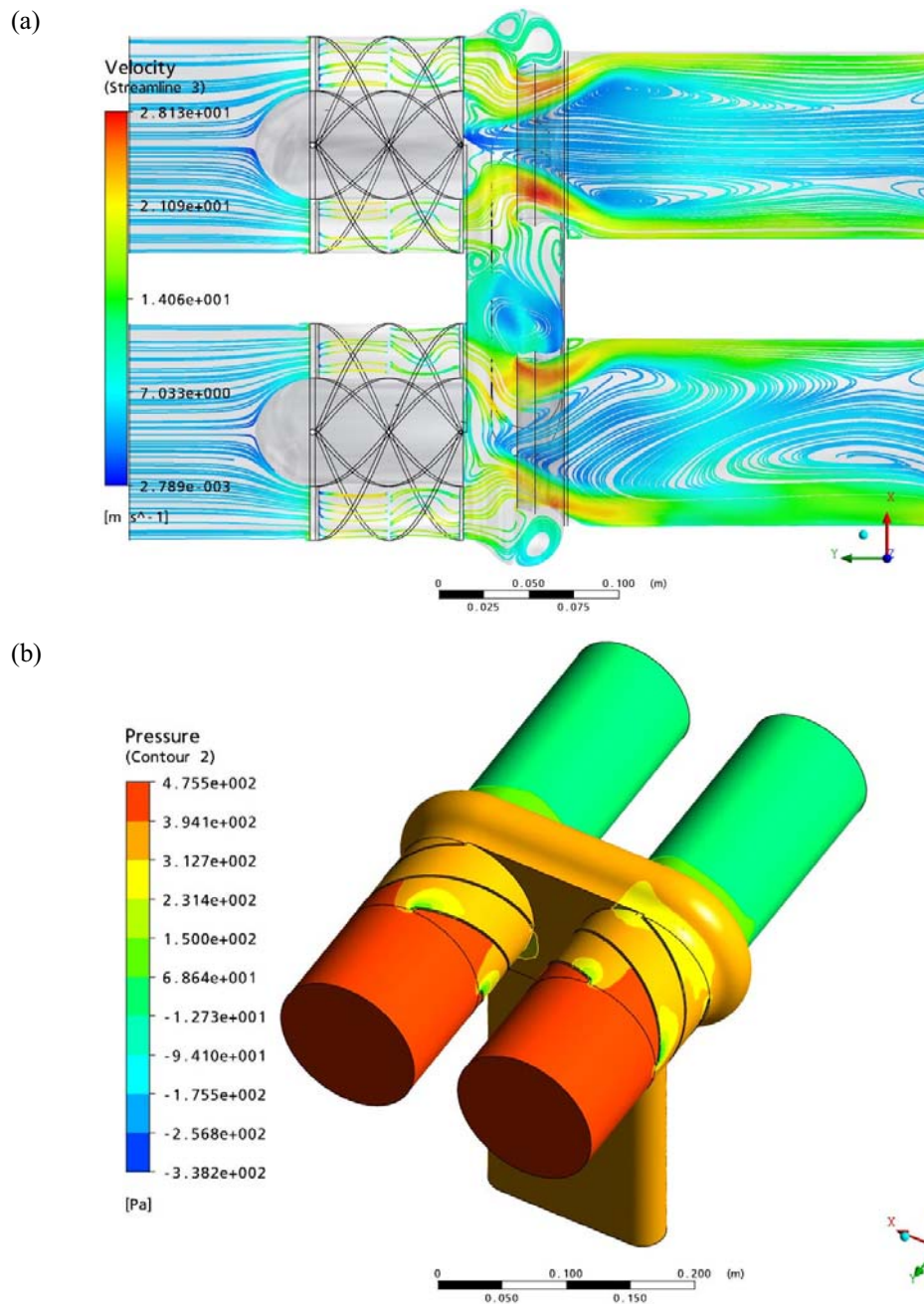


Fig. 4. Result of numerical analysis (a) streamline of cyclone system (b) pressure distribution.

Table 1. Particle removal efficiency (inlet velocity of 5 m/s).

Particle size (μm)	Inlet particle number	Outlet particle number			Efficiency (%)
		Outlet 1	Outlet 2	total	
1–2	1993	452	437	889	55.4
2–3	1991	413	427	840	57.8
3–4	2049	394	372	766	62.6
4–5	1939	291	289	580	70.1
5–6	1980	216	237	453	77.1
6–7	2002	194	209	403	79.9
7–8	1941	151	146	297	84.7
8–9	2010	94	87	181	91
9–10	2095	52	59	111	94.7
total	18000	2257	2263	4520	74.9

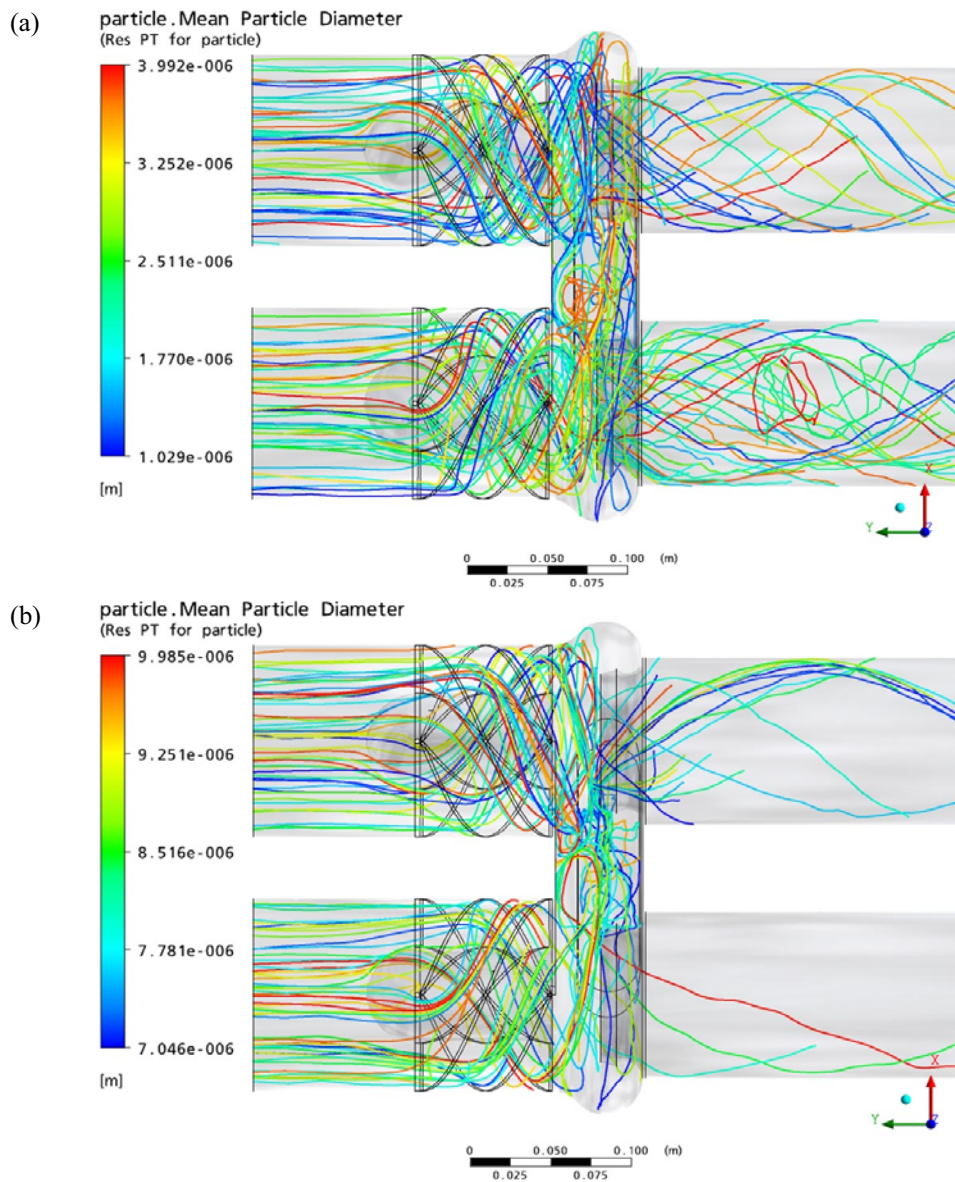


Fig. 5. Particle trajectory at each part of cyclone (a) 1–4 μm particles (b) 7–10 μm particles.

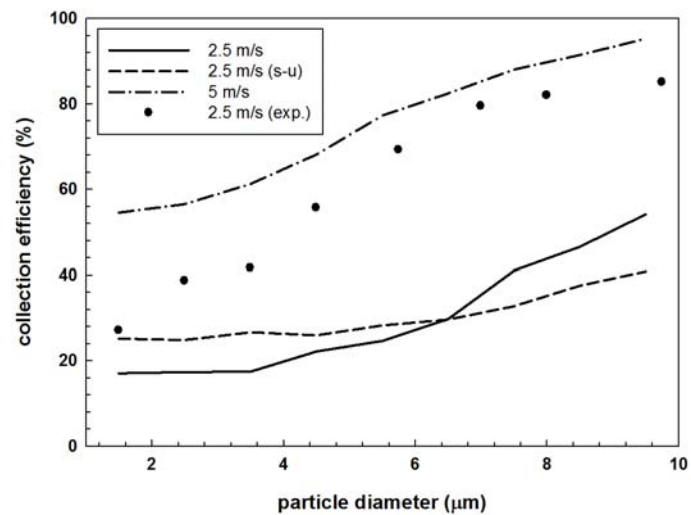


Fig. 6. Particle collection efficiency for different inlet velocity and cyclone scale.

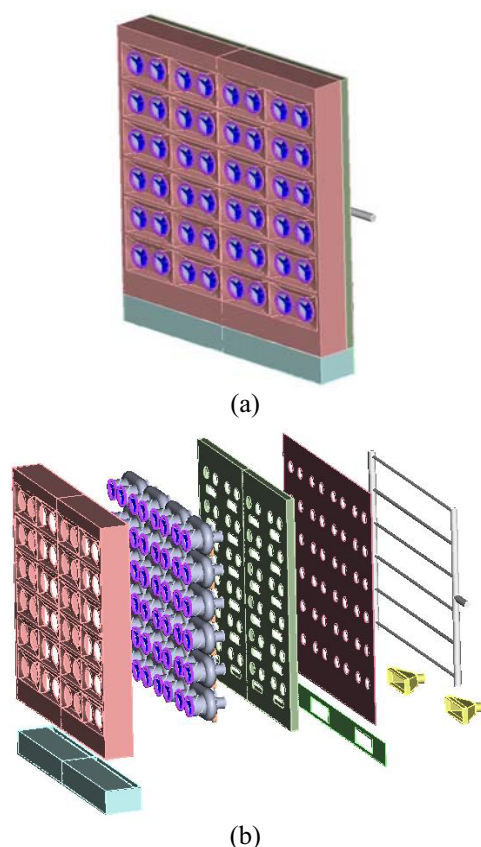


Fig. 7. Design concept for novel air filter applied to the air handling unit (a) panel-type cyclone system (b) system layers.

efficiency was surveyed, and a 37–53% of decrease in collection efficiency were found for different particle sizes. The two times scale-up of the cyclone geometry caused a flat collection efficiency curve with respect to particle sizes. We believe that the novel axial-flow cyclone system is a cost effective and efficient way of removing particulate matters in the size range of 1–10 μm in the AHU of subway stations or buildings. For the verification of panel-type axial-flow cyclone arrays, the pilot scale model is under development.

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