Study of PM2.5 Filtering by Using Climbing Plant Attached to an Architecture

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DOI: 10.14456/built.2020.1
Received: 30/1/2020; Revised from: 20/4/2020; Accepted: 24/6/2020
Print-ISSN: 2228-9135, Electronic-ISSN: 2258-9194, doi: 10.14456/built.2020.1

Abstract

Presently, PM 2.5 (Particulate Matter up to 2.5 micrometers in size) causes health problems and affects human daily life. Previous studies found that some plants help to filter fine particles by trapping dust and particulate matters on their leaves, which can be washed for reuse. This research aims to use the leaves of the Bengal trumpet plant (Thunbergia grandiflora.) adhering to a design architecture to reduce the amount of PM2.5 flowing into buildings. The Bengal trumpet attached to the wire-mesh architecture located in front of the building's door traps PM 2.5 on its leaves. The architecture obstructs the high flowing wind through the door. Research methods include PM 2.5 filtering in the test box, and wind resistance design to reduce wind speed using the Flow Design program. The results showed that Bengal trumpet leaves with a density of 85 leaves per 0.4 square meters could reduce PM2.5 up to 60%. The plant's leaves slow down the air speed and temporary reduce the PM 2.5 concentration for 9-15 minutes. The results of simulation with the Flow design program showed that wire-mesh architecture with half-cylinder form reduces wind speed more than that of cylinder forms for a similar surface area. This research confirms previous findings that plant leaves can trap fine particles. Furthermore, an architecture designed to moderate wind speed in appropriate direction with Bengal trumpet leaves can increase the filtering performance significantly.

Keywords: air pollution, particulate matters, particulate filtering, leaf density

1. Introduction

Air pollution has become a major problem for people living in Bangkok and other industrial cities. Particulate matter with a diameter of up to 2.5 micrometers (PM 2.5) are so small and light that they tend to stay longer in the air than heavier particles. This increases the chances of humans and animals inhaling them into the body .PM 2.5 can bypass the nose and throat and penetrate deep into the lungs, some of which can also reach the circulatory system (Pope et al, 2002). Atmospheric particulate matter deposition in trees and urban forest is an importantmeans of controlling air pollution. (Shannigrahi et al, 2005). The deposition in plants is called dry deposition and it depends on both plant species and aerodynamic conditions. The Bengal trumpet, Thunbergia grandiflora., a climbing plant growing in the hot and humid climate of Thailand, was able to trap particulate of 50-micro meter in diameter effectively (Sunakorn et al, 2016). This study aims to study reduction of PM 2.5 entering the door of a shopping mall by using the Bengal trumpet. The aerodynamics of the designed architecture is taken into account because it promotes turbulent diffusion and particulate deposition on plants.

Literature reviews

Effective mitigation of PM 2.5 and air quality improvement in Europe are presently based on cost-effective models where policies, air quality, greenhouse gases, and economic considerations are integrated (Amann et al, 2004; Amanna et al, 2011; Kunugi et al, 2018). Mitigation policy development requires identification of air pollution sources (Chen et al, 2019). In Bangkok, major sources of PM 2.5 at traffic sites were automobile and biomass burning, contributing approximately 32% and 26%, respectively. At residential sites, biomass burning was the major source of PM 2.5 mass concentrations. (Chuersuwan et al, 2008). Urgent measures to solve the problem of small particles PM2.5 in Bangkok includes strict control of black smoke from cars, trucks and buses. (Department of Land Transport, 2019) From literatures, trees can capture air pollution. The coniferous forests absorbed 21% of NO2, O3, SO2, CO and PM10 (de Jalón et al, 2019) and PM 2.5 (Sun et al., 2014; Yina et al., 2019) A study of loss rate coefficients for PM2.5 depositions on leaf surfaces for 24 hours of artificial plants and real plants showed that loss of PM 2.5 significantly. The real plant with wrinkle and hairy leaves exhibited the highest PM2.5 collection capability during the first 3 hours, but it declined over time due to plants transpiration (Rattanapun et al, 2017).

Particle deposition depends largely on atmospheric, surface, and particle characteristics. The most important atmospheric parameters include wind speed, humidity, stability, and temperature (Pacyna, 2008). The deposition rate or deposition velocity (V_d) of small particle ie. such as PM 2.5 is much slower than large particle size such as PM10 (Wu et al, 2018) Deposition velocity is defined by $F = V_d c$, where F is flux density, v is deposition velocity, and c a form of concentration (Pacyna, J.M., 2008). One way to remove airborne particles from the polluted atmosphere is the turbulent deposition of aerosol particles from an air stream to a surface. The rate of turbulent deposition can be significantly higher than the deposition rates due to diffusion (Sehmel, 1972). The presence of a small amount of surface roughness significantly enhances deposition, especially that of small particles (Guha, 2008; Zhu et al, 2018). Based on this evidence, namely PM 2.5 mitigation using plants and the particle deposition enhancement in the turbulent flow, this study applies the climbing plant attached to designed architecture to reduce air pollution entering the door of a shopping mall. In Thailand, the door of the shopping mall is the entrance of particulate matter flowing into the building because the door usually exposes to traffics, parking lots, and food grilling shops. As shown in Figure 1, the existing exhaust fans draw the outdoor air into the building, enhancing indoor air pollution. This study proposes that climbling plants filter particulate matters before they enter the door.

2. Methodology

2.1 Preliminary study

The area of the selected shopping mall is 8,000-10,000 sq.m. with more than 128 branches in Thailand. In the preliminary study, researchers visited four branches of this shopping mall in Bangkok to collect data on particulate matter concentrations, PM 2.5 and PM 10. The dimensions and design of the existing door of the shopping mall are shown in Figure 2. There are two types of the shopping mall's door: the double-glass door with transition space and the single-glass door without transition space. This study collects data from only the single-glass door type because the single-glass door directly exposes people to outdoor air pollution.

Figure 1. The idea of air filtering infront of the shopping mall's door in this study.

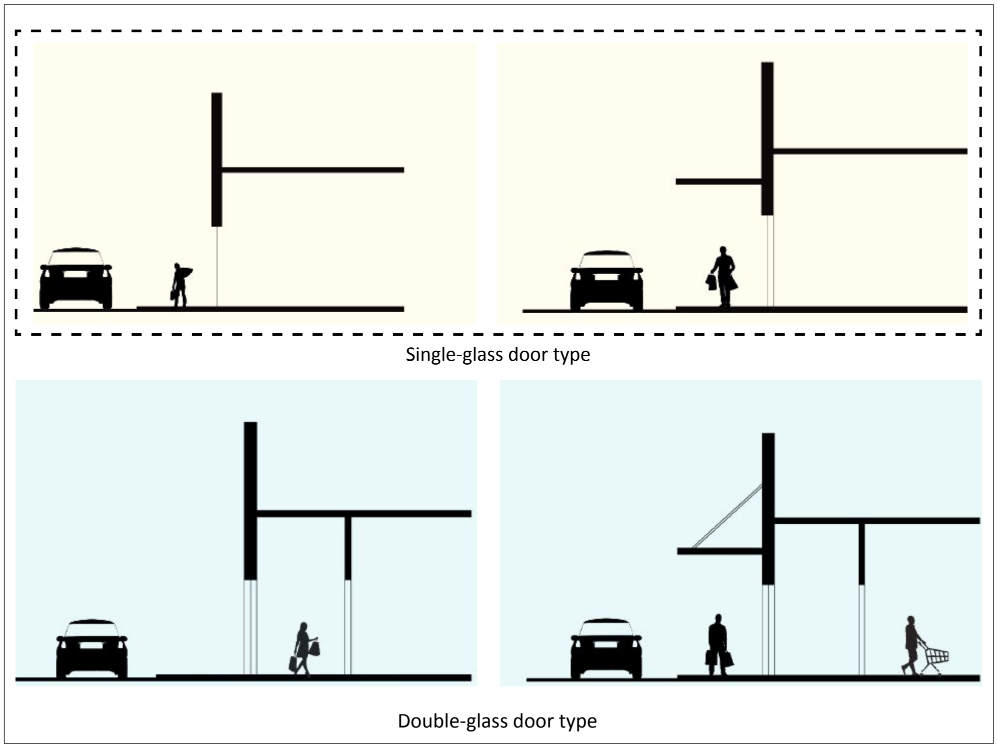


Figure 2. Door types of the shopping mall.

Figure 3 shows the measurement position and the collected data. In this study, two air quality detectors, Hilitand brand, were used to measure particulate matter concentration. The measuring range was 0-500µg/m³ with particle mass concentration error range of ±10%@0-500µg/m³. The air velocity was measured by a hot wire anemometer, Model number AM-4214SD (measuring range 0-25 m/s, accuracy ±0.1 m/s).

The measurement positions were 0.5 m and 2.0 m above the floor both indoor and outdoor. The outdoor measurements were conducted on the pavement in front of the door. The indoor measurements were conducted inside the building, 1.5 m from the door. The results showed that the concentration of PM 2.5 in the outdoor exceeded the healthy limits of 25-50 µg/m³ despite the lower PM 2.5 concentration in the indoor. In addition, we found the PM 2.5 concentration at 2.0 m is higher than that at 0.5 m. The data was collected during 11.00-18.00 every 2 hours. The average concentration of PM2.5 in the four sites is 96.4 µg/m3 and 63.2 µg/m³ in the outdoor and indoor air, respectively. During the field investigation, the air flow into the building when the door is open because there are of the exhaust fans in the building. The measured air velocity at the indoor was 0.9-2.0 m/s.

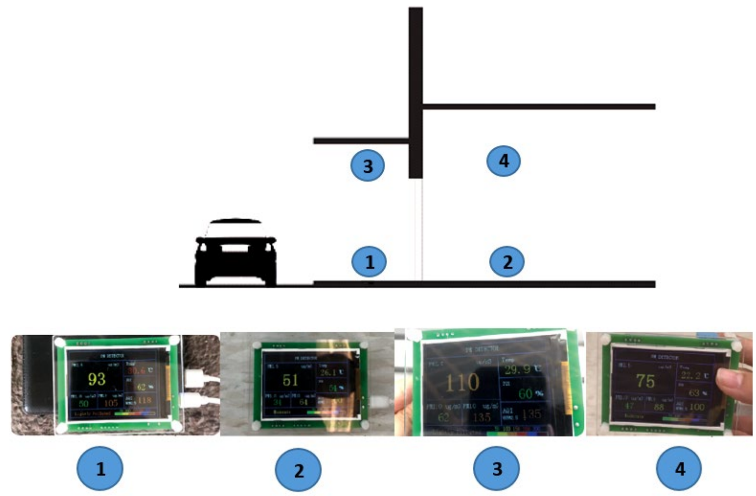


Figure 3. The collected data of PM 2.5 concentration at measuring positions.

0.4-1.0 cm²/leave | 65 leaves/0.4 m² | 85 leaves/0.4 m²

Figure 4. Bengal trumpet leaves and the different number of leaves on the grille.

2.2 Experimental setup with the Bengal trumpet

The leaves of the Bengal trumpet were attached to a grille with an area of 80 cm x 50 cm. The number of leaves varies from 65 and 85 leaves as shown in Figure 4. The grille with attached Bengal trumpet leaves was placed between boxes A and B to filter high air pollution flowing from box A to box B. During the smoke preparation, box A was closed with a wood pane and separated from box B. To start the experiment, box A (80 x 80 x 80 m3) was filled with smoke with PM 2.5 concentration of 350-400 µg/m3 and the smoke source was taken out. The wood pane was opened to let the particulate matter disperse. Initially, box B was filled with the ambient air with PM 2.5 concentration of 65-68 µg/m3. In the first experiment, the PM 2.5 dispersed from box A through the Bengal trumpet by a diffusion process. In the second experiment, the PM 2.5 was forced to flow from box A through the Bengal trumpet to box B by an exhausted fan. Experiment 1 and 2 were repeated two times to confirm the results and the average values of PM2.5 were computed. Figure 5 shows the experimental arrangement of box A and B in this study.

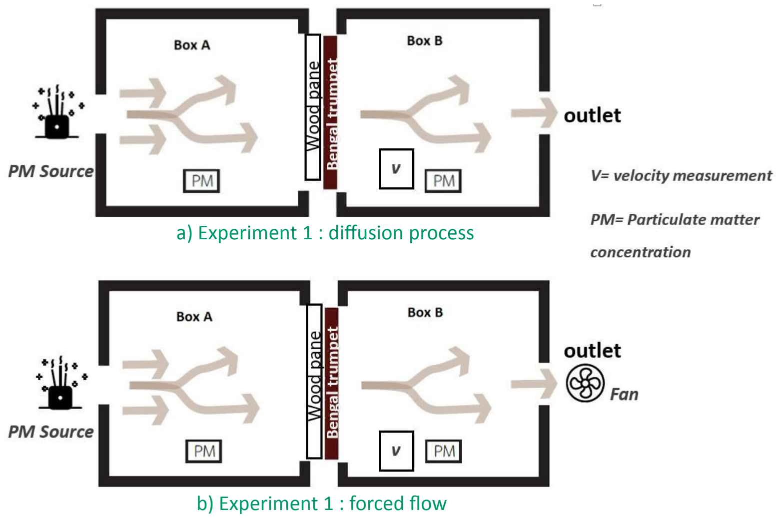


Figure 5. Schematic experimental set up of a) diffusion and b) forced air flows.

Figure 6. Study of the effect of structure forms on the air velocity

2.3 Experiments on the effect of architecture forms on the air velocity

The effect of three architectural forms on air velocity are studied in the experimental chamber as shown in Figure 6. The designed architecture is not only for the climbing plant, but also for enhancing the particulate matter deposition on plant leaves due to air velocity reduction in front of the building's door. The three forms include cuboid, half-cylinder, and cylinder forms. The airflow from Box A passing through the studied forms to box B and exits at the outlet of the latter box. The results of air velocities were measured in box B. PM2.5 particles can be deposited on the surface of this structures. The surface roughness mimics the actual material of the columns. The three forms of vertical structures represent the column forms in front of the building.

2.4 The Flow Design Program

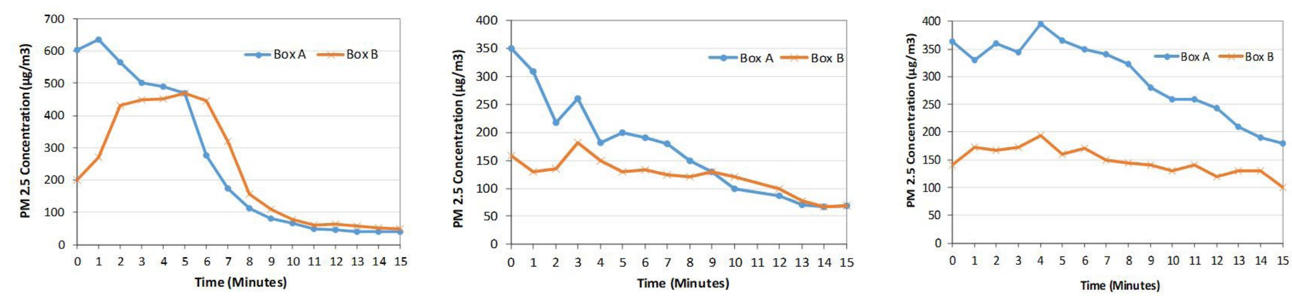
Flow Design is a virtual wind tunnel software for product designers, engineers, and architects. It models airflow around design concepts to help test ideas early in the development cycle. In this study, flow design is used for simulating wind flowing through the designed architecture in front of the shopping mall's door.

3. Results and discussion

The performance of PM 2.5 filtering by the Bengal trumpet leaves are shown and discussed. The effect of air velocity on the particulate flow are studied in terms of percentage reduction of PM 2.5 and the effectiveness of ventilation of the building.

3.1 PM 2.5 filtering via the diffusion process

Figure 7a shows the results of PM 2.5 concentration diffusion from box A to box B without the plant-leaves grille. After the wood panes are opened, particles disperse from box A to box B. The concentration of PM 2.5 in box A decreases while it increases in box B. The concentration in the two boxes are equal after four to five minutes.



(a) Without plant's leaves (b) Filtered with 65 leaves/0.4 m² (c) Filtered with 85 leaves/0.4 m2

Figure 7. The average PM 2.5 concentration in the diffusion process.

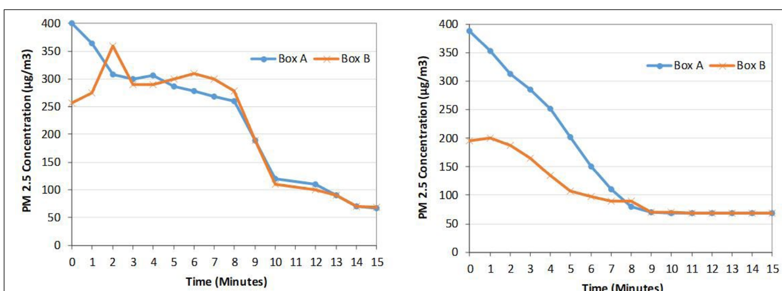
After that, the concentration of PM 2.5 in box B is higher than that in box A because most of the particles that reach box B exit at the outlet. For this experimental setup, it takes around 15 minutes to let the PM 2.5 concentrate in the two experimental boxes until they reach 68 µg/m3 in the ambient air. The concentration of PM 2.5 in the air after filtering with 65 and 85 Bengal trumpet leaves/0.4 m² are shown in Figure 7b and 7c, respectively. With 65 leaves/0.4 m², the PM 2.5 concentration is almost consistent around 125-150 during the first 9 minutes. After that, the concentration in box B is comparable to that in box A. With 85 leaves /0.4 m², the particulates are obstructed in box A and stay there longer than they do in box B. During the first six minutes, the concentrations of PM 2.5 in box A and box B are quite stable at 350 and 175 µg/m3, respectively. In 15 minutes, the concentrations of PM 2.5 in box A and box B reduce gradually to 180 and 100, respectively. The percentage differences between box A and box B in the experiment with 65 leaves and 85 leaves are 20-57% and 48-61%, respectively. This experiment shows that high leave density effectively blocks the penetration of PM 2.5.

3.2 The PM 2.5 filtering via the forced airflow

Figure 8 shows the results of PM 2.5 concentration using an exhaust fan to assist airflow. The high air velocity penetrates through the grille with 65 leaves due to large voids in the 65-leave grille. The PM 2.5 concentration in the two boxes are similar as shown in Figure 8a. With 85 leaves in the filtering grille, the percentage difference of PM 2.5 in box A and box B are 18-50% during the first eight minutes as shown in Figure 8b. This experiment shows that the PM 2.5 concentration can be reduced rapidly with higher airflow through the filtering area.

3.3 Air velocity after filtering with plant leaves

With only 65 leaves in the filtering grille, there are large voids presented in the grille. The average air velocity at box A and box B is 1.12 m/s and 0.5-1.0 m/s, respectively. The high air velocity brings higher PM 2.5 concentration to box B and diminishes the filtering performance of the plant leaves.



(a) Filtered with 65 leaves/0.4 m² (b) Filtered with 85 leaves /0.4 m²

Figure 8. The average PM 2.5 concentration in the forced airflow.

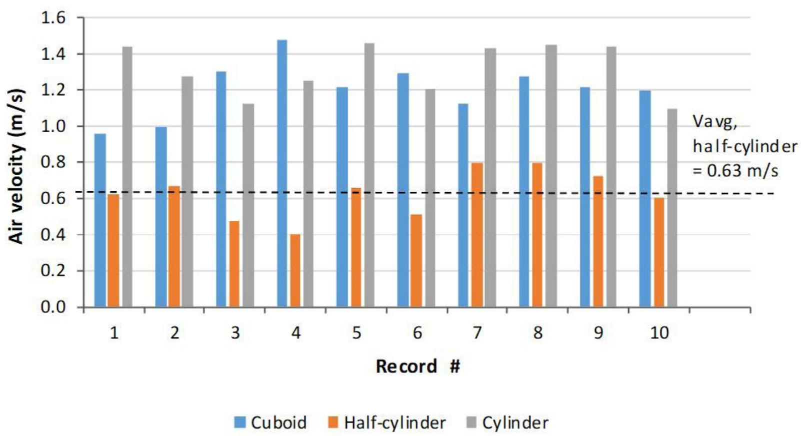


Figure 9. Air velocity drawn through different architectural forms.

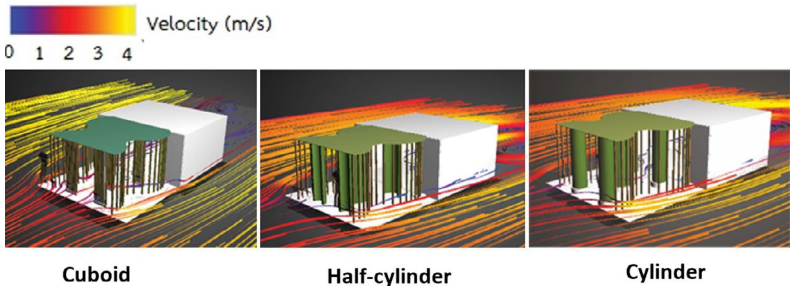


Figure 10. Air velocity streamlines of different architectural forms.

With the thick filtering of 85 leaves in the grille, the average air velocity in box B is 0.0-0.4 m/s. Under forced airflow, the performance of filtering grilled with thick leaves can last for 8 minutes.

3.4 Air velocity drawn through different architectural forms

The results of the experiment with different architectural form are the measured air velocities in box B. The air velocity was recorded every one minute for 10 minutes. The results are shown in Figure 9. The average air velocity when air flows through the half cylindrical forms is less than for the other two forms. The results in the previous experiment show that less air velocity enhances PM2.5 deposit on the plant leaves. Therefore, the cylindrical form is selected to design the meshed architecture.

3.5 Architectural designs for the climbing plant

Design schemes Figure 10 shows the results of velocity fields of different architectural forms. The air velocity in front of the building is 1-0.2.0 m/s. The effect of air architectural forms on air velocity can be explained here via the graphic illustration of air velocity streamlines. The air flowing into the wire-mesh architecture with cuboid pillars partly collides with the sharp edges and increase air velocity. The air flowing through the cylinder pillars makes a detour around the architecture before entering the building. The air flowing through half-cylinder pillars was trapped in the curves and air velocity reduces.

For architecture design in front of the shopping mall, the distances between pillars are crucial. In this study, the distance between two pillars of 2.5 m is designated for humans and shopping carts. Figure 11 shows the simulation results of the shopping mall's front façade with the designed architecture. The simulation results show that a high-depth roof plays an important role in wind capturing as shown in Figure 11b. The roof with large front area slows down the incoming wind and be attaching area for plants that help prevent particulate matter from entering the door.

The final design of the wire-mesh architecture with Bengal trumpet is shown in Figure 12. According to this figure, the number of leaves is 85 leaves/0.4 m^2 or 212 leaves/m^2. The structure span is 15 m and 5 m depth. Wood and artificial wood made of composite materials are recommended for the structure. Wire meshes with 20 cm x 20 cm are needed to hold the climbing plant. The watering system is also required to feed the plant and to wash out the dust and particulate matter from the plant. The design in Figure 12, with the Bengal trumpet hanging on top of the entrance, differs from those in the experimental design. With this design, the Bengal trumpet leaves also exposed to the outdoor air but it has less chances to filter out the air which is coming in to the shopping mall. In this study, the columns and thick roof in front of the building play an important role in dispersing the wind and increasing the chance PM2.5 contacting with the leaves.

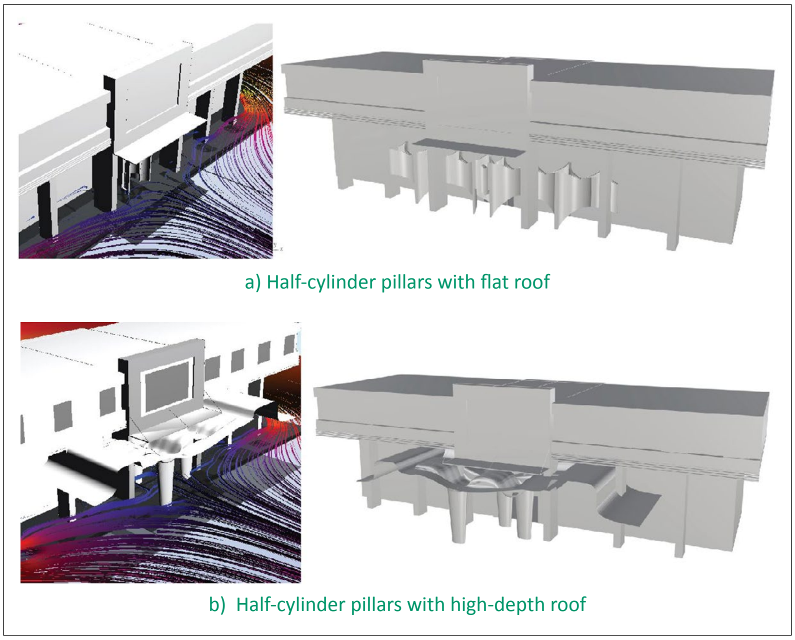


Figure 11. Simulation results of streamlines in two design schemes

4. Conclusions

Air pollution is a severe problem in many countries. Much research exists on capturing particulate matter by plants. This study proposes using a climbing plant named Bengal trumpet (Thunbergia grandiflora.) attached to wire-mesh architecture to reduce PM 2.5 (Particulate Matter up to 2.5 micrometers in size) flowing into the door of a shopping mall. The concentration of PM 2.5 in the shopping mall was less than that outside of the mall, but the concentration exceeds the healthy limit. This study shows that dense plant leaves can block PM 2.5 and reduce the amount of it that enters the building by 50%. The plant's leaves block the air flowing into the building and the filtering performance drops after 9-15 minutes. The filtering performance is the combined effects of both PM 2.5 deposition on the plant leaves and the low airflow into the building. Reduction of air velocity is important because low air velocity tends to increase deposition and prolong the appearance of PM2.5 in the building. The appropriate architectural form that allows turbulent airflow assists the air filtering. This study recommends a semi-outdoor space in front of the shopping mall's door with climbing plant on the pillars and on the roof for PM 2.5 mitigation. Deposition of PM 2.5 on plants leaves is temporary; water is also needed to wash out the deposited PM 2.5 and then reuse the plant.

a) Perspective

b) Front view

c) Side view

d) Structure and meshes

Figure 12. The designed architecture with the Bengal trumpet.

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