

Computational Fluid Dynamics Analysis of Green Filtration Systems for Air Pollution Control

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Abstract

Air pollution is one of the crucial environmental and public health concerns that emerged due to an increase in industrial activities, greater usage of transportation, and burning of fossil fuels as well. Due to this severe problem, air filtration systems such as plant-based filters have been found to be eco-friendly solutions for the reduction of urban pollution. The objective of the present work is to investigate the effect of different plant filter panels, such as blocking, parallel, and zigzag, at four different air flow speeds of 0.5, 1, 1.5, and 2 m/s on the air flow characteristics as well as on the dispersion of pollutants. The outputs of the CFD investigations were represented in the form of particle pathlines based on PM10 particles, zones of recirculation, patterns of airflow, and profiles of velocities for all plant filters. It was found that maximum capturing of pollutants occurred, and a decrease in airflow occurred for the blocking configuration. On the other hand, parallel plant panels encountered low loss of pressure with better and smoother flow of air. In addition to this, the greatest turbulence, again and again, change in flow direction, and recirculation was gathered for the zigzag configuration. Peak mixing of air flow and maximum capturing of pollutants occurred for the case of zigzag panels. Hence, these CFD investigations have confirmed that optimized plant-based filtration systems help in creating a sustainable environment.

Keywords: Computational Fluid Dynamics, Air Pollution Mitigation, Plant-Based Filtration, PM10 Dispersion, Urban Air Quality, Green Infrastructure, CFD Simulation

1. Introduction

Rapid growth in industrial activities, rapid urbanization, and a rapid increase in the number of automobiles, leading to a heavy increase in transportation and a huge increase in energy demand at the global level, all gave rise to a global issue known as Air pollution. Burning of fossil fuels, exhaust generated from industries, emissions coming from vehicles, an increase in urbanization activities, at the same time, cutting of several trees have created a huge opportunity for the generation of various air-polluting pollutants in terms of sulphur oxides, carbon monoxide, particulate matter, and volatile organic compounds, and for their release in the environment. In the context of the various types of respiratory diseases, heart-related diseases, brain-related diseases, as well as environmental pollution, air pollution generated from automobile exhaust during heavy traffic was considered as one of the biggest contributors to air pollution [1,2]. Besides this, it was also recognized that, due to heavy production and use of automobiles for transportation, the quality of air degraded to very poor levels, in the name of industrialization and for economic benefits [3,4]. In the context of air pollution generated via automobiles, it was seen that mostly diesel engines were the major contributors to air pollution in terms of various types of air pollutants, and this urges the necessity for the development of exhaust treatment systems for sustainable growth [5]. In the recent past, it was discovered that air quality can only be controlled effectively by adopting and enforcing different kinds of air pollution mitigation techniques, as well as environmental policies and norms [6]. Besides this, it was also realized that

application of various sensor-based measurements of air pollutants, as well as taking help of unmanned aerial vehicles, helps in differentiation of pollutant levels in various types of environments [7].

In order to tackle the problems encountered due to the ill effects of air pollution, researchers in the past mainly concentrated on three major methodologies, namely intelligent monitoring systems, technologies for emission control, and smart environmental management. Researchers proposed Internet of Things-enabled monitoring systems and employed air pollution detection systems for real-time monitoring of pollutants [8,9]. In order to reduce the detrimental effect of transportation systems, various types of electronic systems were developed for optimization of fuel usage as well as for reduction of emissions levels [10].

Besides air pollution control techniques, researchers also worked on some conventional as well as advanced air pollution strategies at a global scale. In this context, researchers identified various techniques such as green infrastructure development, emission regulations, traffic management systems, industrial pollution control technologies, urban vegetation barriers, and renewable energy-based mitigation approaches [11–16]. Again, in this scenario, researchers have found that due to government intervention, intricate policies were designed for pollution control for sustainable urban development for improved health [12,13]. Researchers have also gathered that there is an interconnection between the nature of air pollution and the management of climate change through devising climate-responsive pollution control strategies [17-20].

In the recent past researchers have realized that computational fluid dynamics is one of the prominent solutions as a tool for quantifying and analyzing the characteristics of air flow, dispersion behavior of pollutants, effectiveness of ventilation systems, as well as for mitigation performance for intricate environmental systems. Besides this it was also identified that CFD based approaches are quite useful for examining microscale airflow distribution, mechanisms of pollutant transport, characteristics of turbulence, and interaction between air pollutants and physical barriers within urban and indoor environments.

In one of the earlier investigations on the examination of capabilities of computational fluid dynamics in the context of prediction of indoor air dispersion, evaluation of content of volatile organic compounds, as well as for transportation of formaldehyde within residential buildings [21]. In another investigation using a CFD-based approach, researchers adopted Risk-based prioritization methods based on CFD numerical simulation for risk assessments in environmental scenarios as well as for ventilation optimization [22]. Besides this, researchers have employed CFD approaches even for the simulation of pollution control in hospitals, industrial buildings, and ventilation systems [23]. Besides, these researchers also comprehensively studied the importance of the application of computational fluid dynamics for the analysis of building ventilation, analysis of urban climate, and environmental pollution control [24].

Out of these various air pollution mitigation strategies, it was gathered that plant-based air filtration systems emerged as an outstanding approach due to various inherent reasons such as minimized energy demands, eco-friendliness, and capabilities of carbon sequestration, and for improvement in air quality. It was realized that for effective control of air pollution problems, strategies of employing vegetation barriers and plant-based filtration systems, which in turn help in the reduction of pollutant concentrations through deposition, adsorption, interception, diffusion, and absorption mechanisms [11-20]. Thus, it was gathered that green filtration techniques are highly effective in air pollution control as compared to other available options of chemical and mechanical treatment systems for the management of urban air quality.

It was gathered that in spite of increasing application of vegetation-assisted pollution strategies, the majority of studies focused on employment of large-scale urban green infrastructure, green walls, and basic interactions between vegetation systems and airflow [21-30]. Besides this, it was also gathered that mainly earlier investigations focused on the reduction of environmental pollutants and did not focus exclusively on aerodynamic performance analysis of plant-based filtration systems [21-30]. In addition to this, very restricted CFD-based studies were analysed for comparative analysis of different plant panel configurations under controlled airflow conditions [21-30]. It was gathered that the effect of different plant-based filtration systems upon airflow distribution, turbulence intensity, pressure drop, pollutant residence time, and filtration efficiency was still less explored [21-30]. The present study

aims to investigate airflow behavior, pollutant dispersion patterns, turbulence generation, and filtration performance associated with using blocking, parallel, and zigzag panel arrangements under different inlet airflow conditions.

2. Methodology

2.1 Physical and Numerical Modeling

The present work deals with CFD analysis of plant-based filtration systems in order to investigate the effect of different panel configurations namely blocking, parallel, and zigzag panel configurations on the output characteristics on airflow characteristics and PM10 pollutant dispersion behavior. The CFD simulation was conducted using ANSYS Fluent 22.0 under steady-state conditions for three different plant filtration systems.

In the present work, PM10 particles were modelled by using a multiphase Eulerian framework in which air was treated as the primary continuous phase. The present study employs the standard $k-\epsilon$ turbulence model to simulate turbulent airflow behavior for establishing indoor and environmental airflow simulations. Besides this, the energy equation was also considered to take into account the effect of temperature on airflow transport and pollutant dispersion. Table 1 shows the various thermo-physical properties that are essential for CFD simulation.

Table 1. Properties of air used for CFD simulation

S.No.	Properties of Air	Value
1	Density	1.225 kg/m ³
2	Dynamic viscosity	1.7894×10^{-5} kg/m·s
3	Thermal conductivity	0.0242 W/m·K
4	AQI	90
5	Initial PM10 concentration	80 µg/m ³

2.2 Boundary Conditions

In present CFD simulations, four different velocities of air were considered, 0.5-2.0 m/s, in order to assess the effect of airflow intensity on pollutant transport and filtration performance. Besides this, during CFD simulation, atmospheric conditions of inlet temperature of 298.15 K (25°C) and pressure of 101325 Pa were considered. The diameter of the hydraulic opening was considered as 0.1 m for the inlet and outlet. A gauge pressure of 0 Pa was considered at the outlet region.

Table 2. Boundary conditions used in CFD analysis

Plant Configuration	AQI	PM10 (µg/m ³)	PM10 (kg/m ³)	Inlet Velocity (m/s)	Inlet Temperature (K)
Blocking Panels	90	80	8×10^{-8}	0.5, 1.0, 1.5, 2.0	298.15
Zigzag Panels	90	80	8×10^{-8}	0.5, 1.0, 1.5, 2.0	298.15
Parallel Panels	90	80	8×10^{-8}	0.5, 1.0, 1.5, 2.0	298.15

2.3 Numerical Solution and Post-Processing

In the present CFD simulation, Finite volume method was considered for the solution of governing equations for mass, momentum, energy, and turbulence based on a simple algorithm. For the purpose of discretization, body-force schemes and second-order upwind schemes were utilized for pressure, momentum, and energy equations, respectively. After the CFD simulation, airflow velocity contours, PM10 particle pathlines, velocity vector

trajectories, turbulence characteristics, and velocity distribution profiles were taken as major outputs.

3. Results and Discussion

3.1 Blocking Panel Arrangement

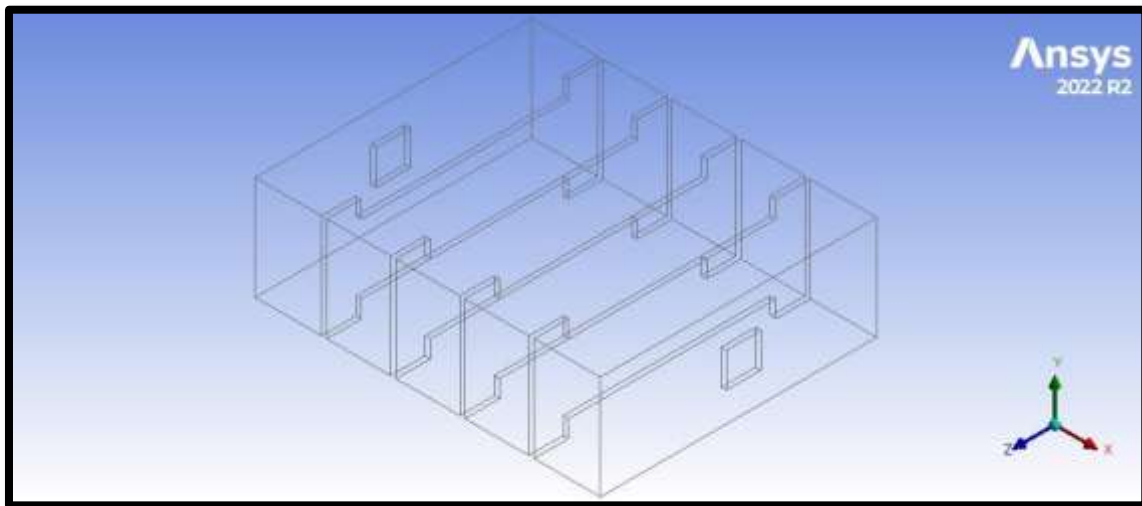


Figure 1. Blocking panel CAD model

Figure 1 shows the isometric view of the CAD model of the blocking arrangement. In this configuration, panels were arranged normal to airflow, which produced maximum air flow and reduced peak pollutants restriction.

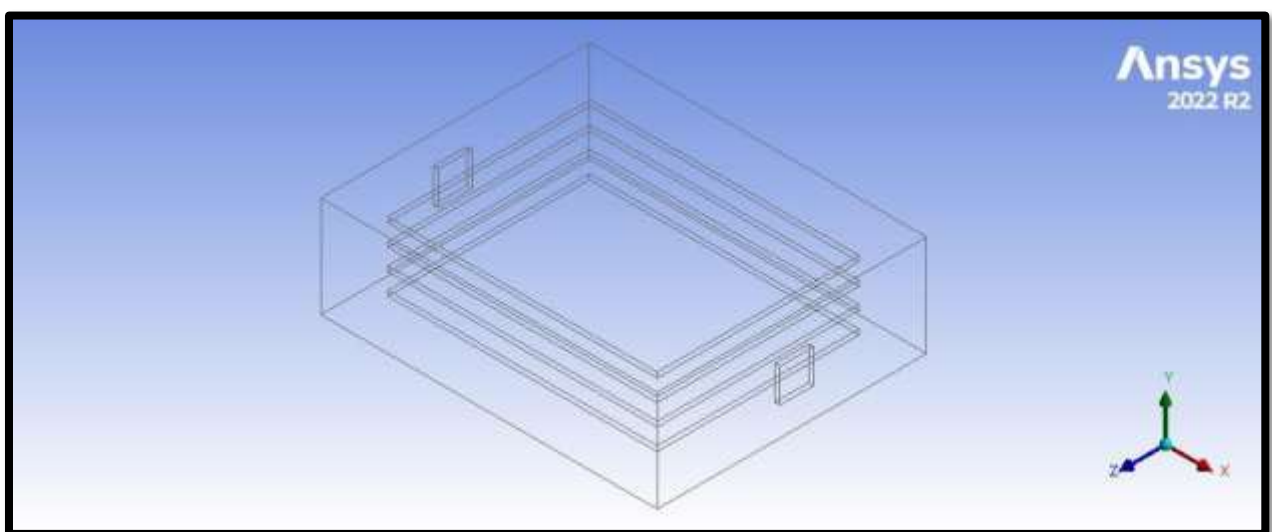


Figure 1. Air-Filtration-Plants-parallel panels-cad-model-isometric view

Figure 2 shows the CAD model of the parallel plant panel arrangement. In this position, the panels are aligned parallel to the airflow direction and it allowed better air passage along with some restriction.

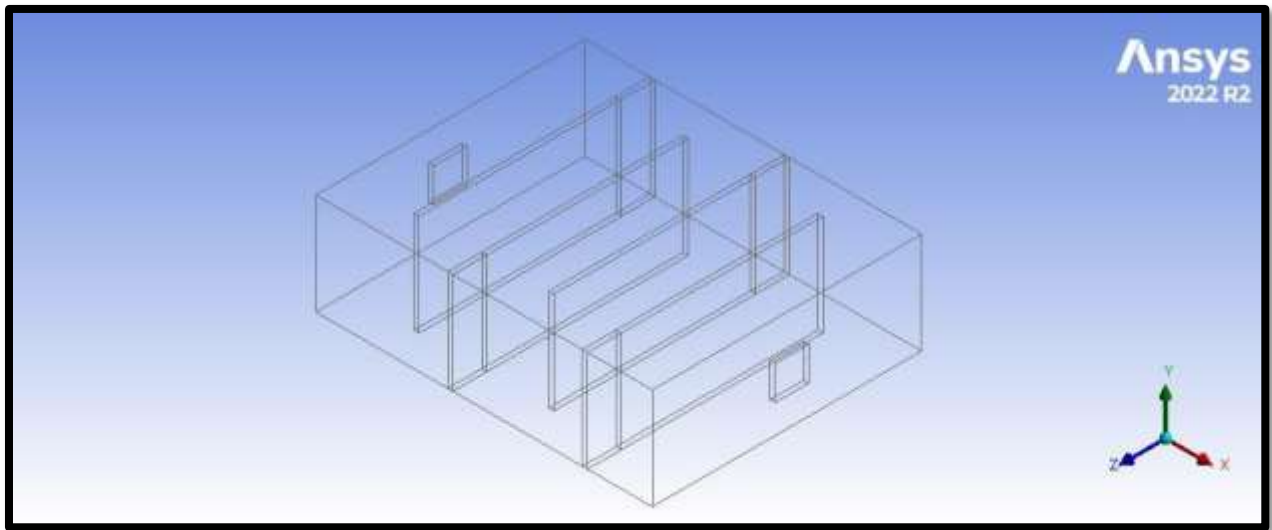


Figure 2. Air-filtration-Plants-zigzag-panels-cad-model-isometric view

Figure 3 shows the zigzag plant panel configuration, which was designed to increase mixing of airflow and encounter various pollutant interactions through continuous direction changes. In this type of flow increases turbulence was obtained.

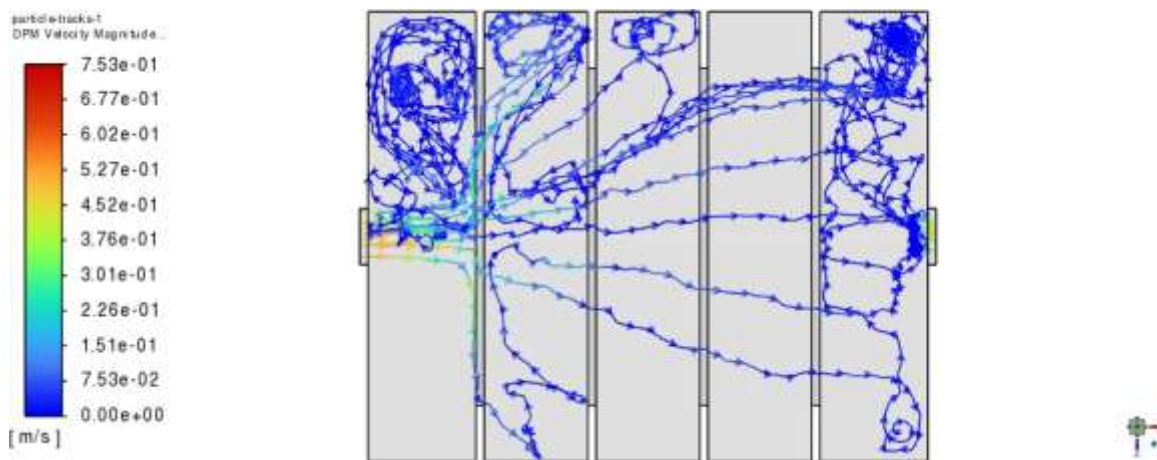


Figure 3. Air-filtration-Plants-Blocking panels-v-.5-pm10-pathline-top view

Figure 4 shows the blocking panels for the inlet velocity of 0.5 m/s. It was gathered that at an inlet velocity of 0.5 m/s, the PM10 particle pathlines indicate relatively smooth airflow movement through the filtration zone with moderate recirculation regions around the plant panels. It was gathered that low velocity allows longer particle residence time, which in turn increases pollutants restriction and efficiency of filtration.

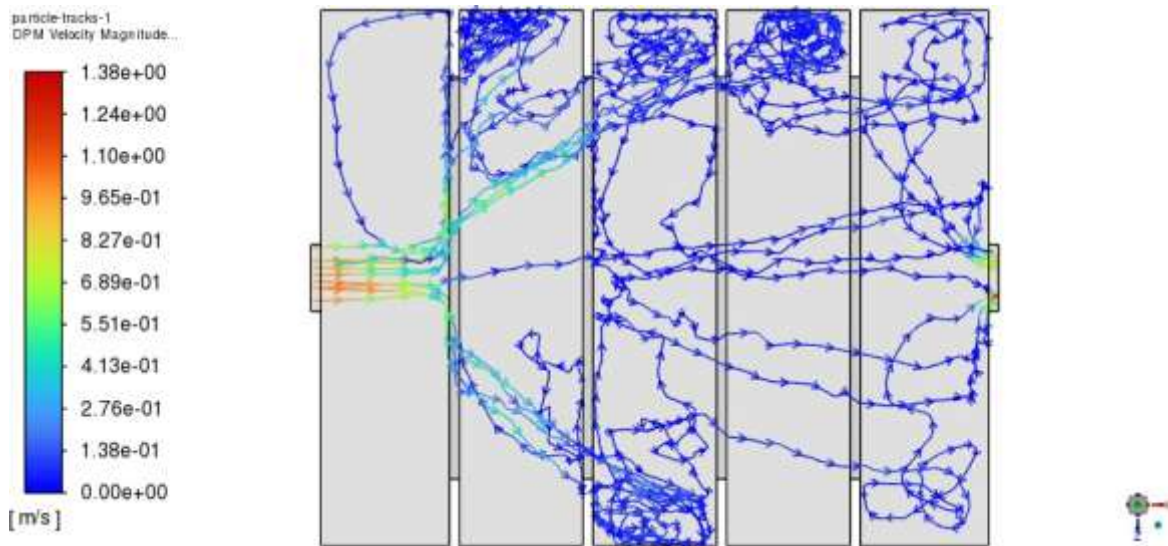


Figure 4. Air-Filtration-Plants-Blocking panels-v-1-pm10-pathline-top view

Figure 5 represents the configuration of blocking panels with an inlet velocity of 1 m/s. It was gathered that at 1 m/s, a greater velocity results in greater momentum and results in deeper contact of air and the panels of vegetation. It was also found that at the downstream of the panels, a medium level of turbulence and regions of wake, which in turn causes enhanced dispersion of particles and better mixing through this filtration system.

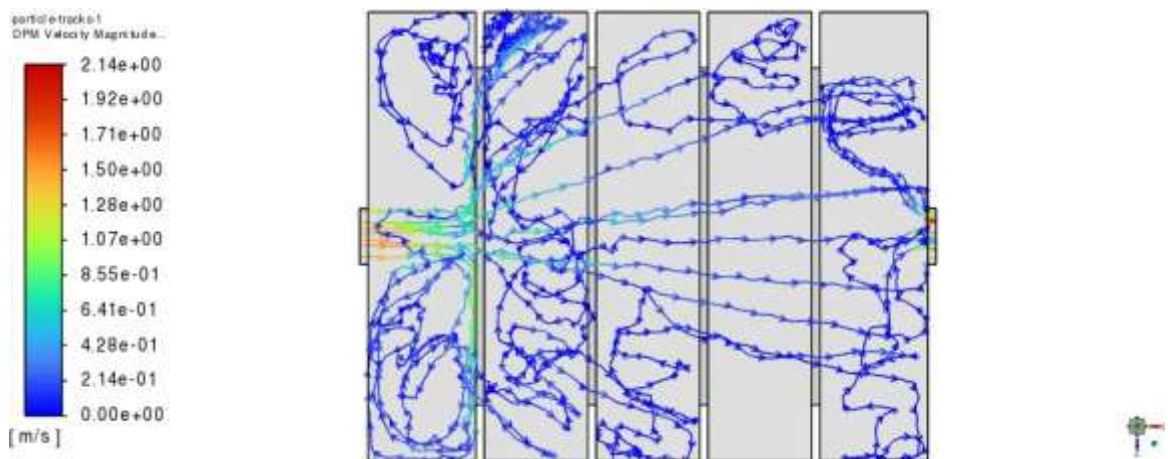


Figure 5. Air-Filtration-Plants-Blocking panels-v-1.5-pm10-pathline-top view

Figure 6 shows the blocking panels for an inlet velocity of 1.5 m/s. It was observed that the airflow created larger recirculation zones and much stronger turbulent vortices around these blocking panels. It was important to note that, while pollutant mixing has increased considerably, high velocity reduces the residence time of particles and, in turn, decreases the effectiveness of filtration for fine particles.

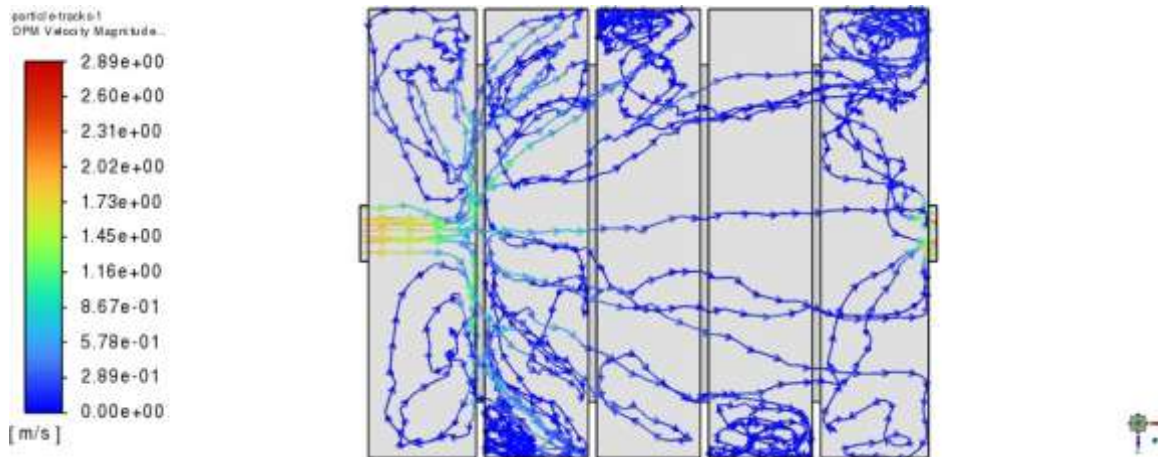


Figure 6.Air-Filtration-Plants-Blocking panels-v-2-pm10-pathline-top view

Figure 7 shows the blocking panels at an inlet velocity of 2 m/s, in which the formation of a wake was visualized behind the panels. It was realized that due to an increase in forces, the pollutants got dispersed along the vegetation panels and, in turn, caused a reduction in pollutants. Besides this, severe changes in velocity and pressure were recorded at increased velocities.

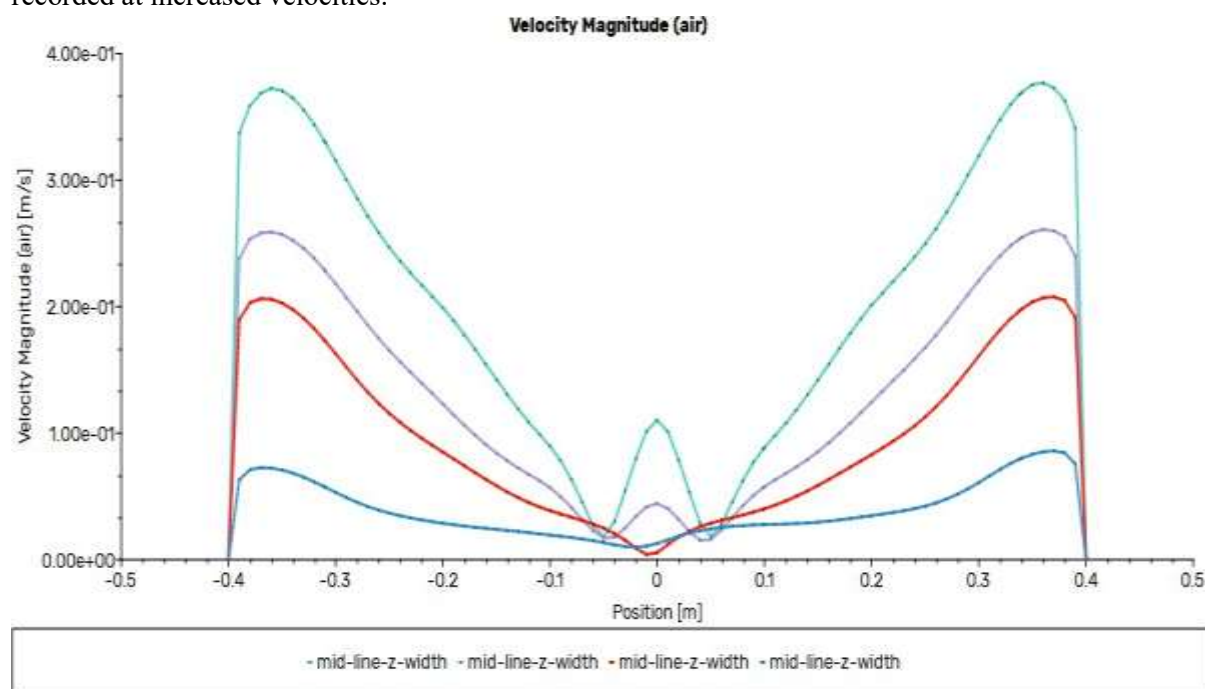


Figure 7.Air-Filtration-Plants-Blocking panels-v-.5-1-1.5-2-vel-graph-mid-line-z-width

Figure 8 shows the velocity profile for blocking panels, in which it was gathered that this graph along the midline width exhibits a variation of progressive velocity with an increment in inlet airflow velocity. Reduction in velocity near the plant panels was gathered for blocking panels via direct obstruction effects. It was seen that higher velocities, very high velocity gradients, and localised turbulence regions were created downstream of filtration systems.

3.2 Parallel Panel Arrangement

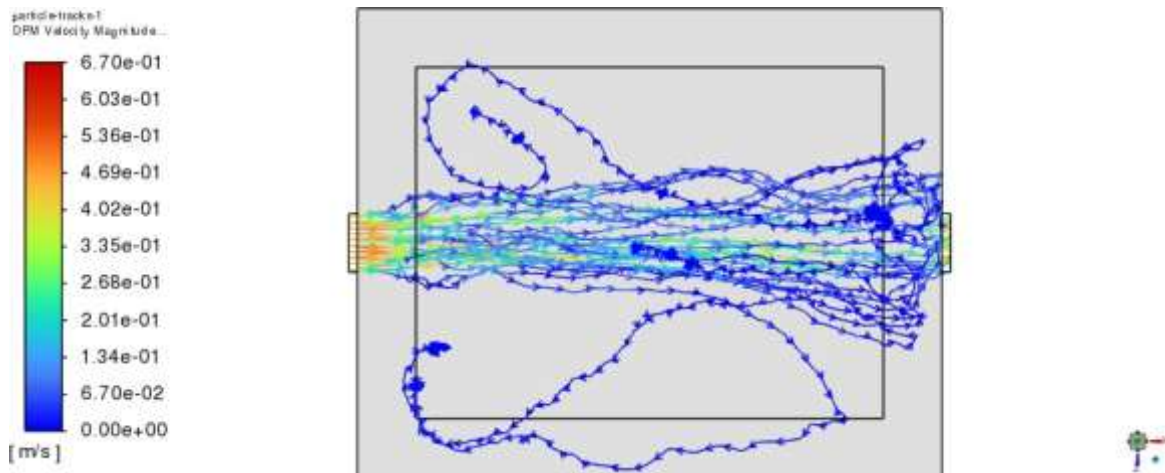


Figure 8. Air-Filtration-Plants-parallel panels-v-0.5-pm10-pathline-top view

Figure 9. Parallel panels at inlet velocity 0.5 m/s. At 0.5 m/s inlet velocity, the airflow remains relatively uniform between the parallel channels with limited turbulence generation. PM10 particles follow streamlined trajectories, indicating stable airflow conditions and comparatively lower pressure drop across the filtration domain.

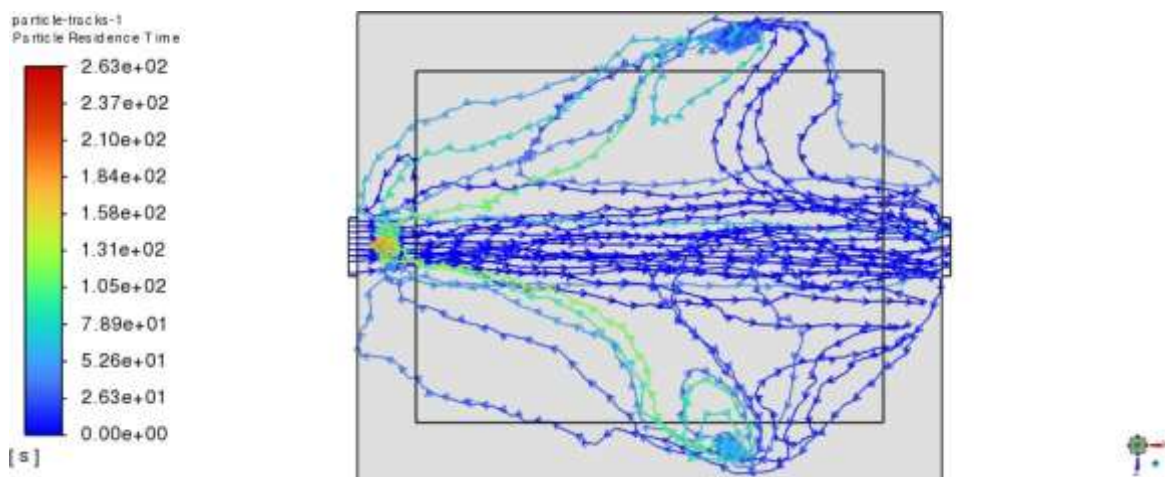


Figure 9. Air-Filtration-Plants-parallel panels-v-1-pm10-pathline-top view

Figure 10 exhibits the parallel panels at an inlet velocity of 1 m/s. It was gathered that at 1 m/s inlet velocity, there are channeling effects which occurred due to the occurrence of medium acceleration of airflow between the gaps of parallel panels. It was also noticed that there is an improvement in the interaction of air and pollutants, and besides, there is the formation of localized vortices along the edges of panels, which actually represents stable flow.

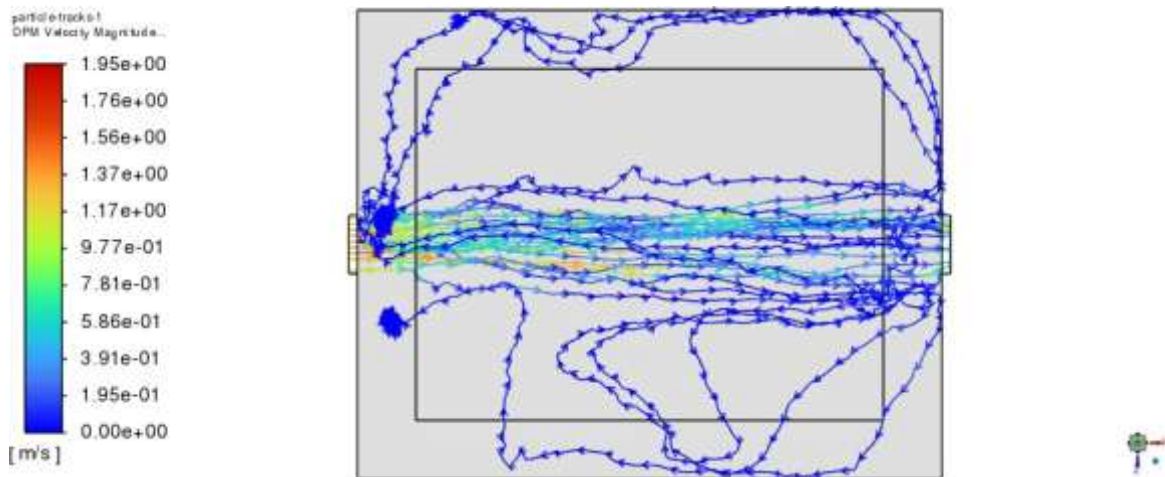


Figure 10. Air-Filtration-Plants-parallel panels-v-1.5-pm10-pathline-top view

Figure 11 exhibits parallel panels at an inlet velocity of 1.5 m/s, and it was gathered that there is an increment in turbulence for airflow in the regions of the channels. An increment in dispersion of pollutants was gathered owing to velocity gradients, and the formation of a wake was found along the downstream of panels.

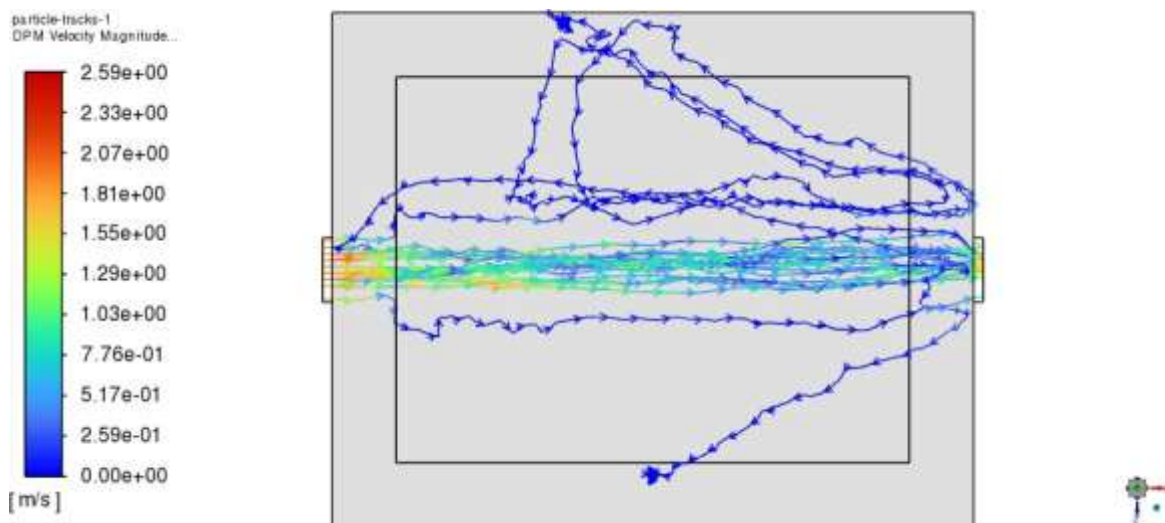


Figure 11. Air-Filtration-Plants-parallel panels-v-2-pm10-pathline-top view

The figure 12 shows the parallel panels at an inlet velocity of 2m/s. It was gathered from Figure 12 that there is a significant increment in acceleration for airflow via parallel configuration, which in turn created zones of recirculation and increased turbulence. On the contrary, it was also realized that the heavy obstruction of flow got reduced due to the configuration available in streamline form when it is compared with blocking panels.

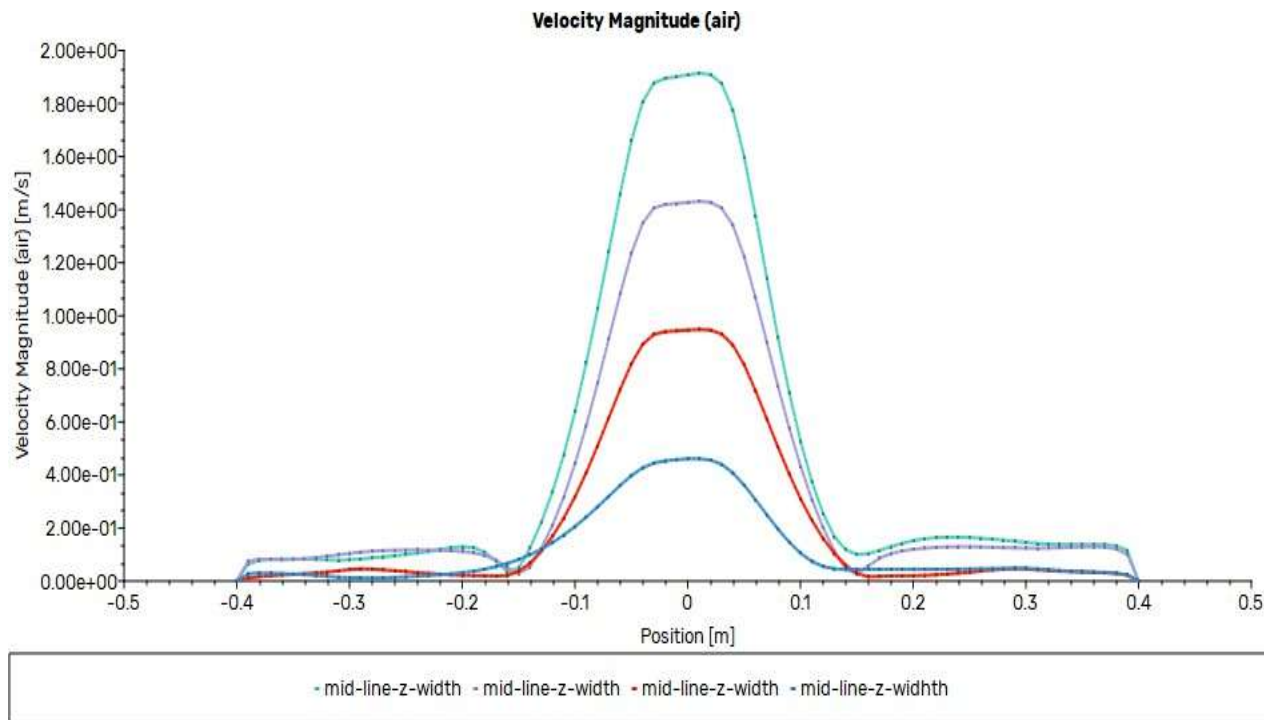


Figure 12. Air-Filtration-Plants-parallel panels-v-0.5-1-1.5-2-vel-graph-mid-line-z-width

Figure 13 represents the velocity profile for parallel panels, which exhibited a smoother distribution of velocity across the midline section. It was gathered that in this type of geometry, in channelized form, it aids in maintaining the movement of air flow in stabilized form, but at the same time maintains reduced pressure loss and also generates medium turbulence along the filtration panels. The channelized geometry promotes stable airflow movement with lower pressure loss while maintaining moderate turbulence generation within the filtration region.

3.3 Zigzag Panel Arrangement

Figure 14 shows the zigzag panels at an inlet velocity of 0.5 m/s, in which controlled recirculation zones nearside of stumpled panels. It was important to notice that in these cases, due to the increment in the length of the path, the airflow residence time has increased, and contact of particles with the surfaces of vegetation was increased considerably.

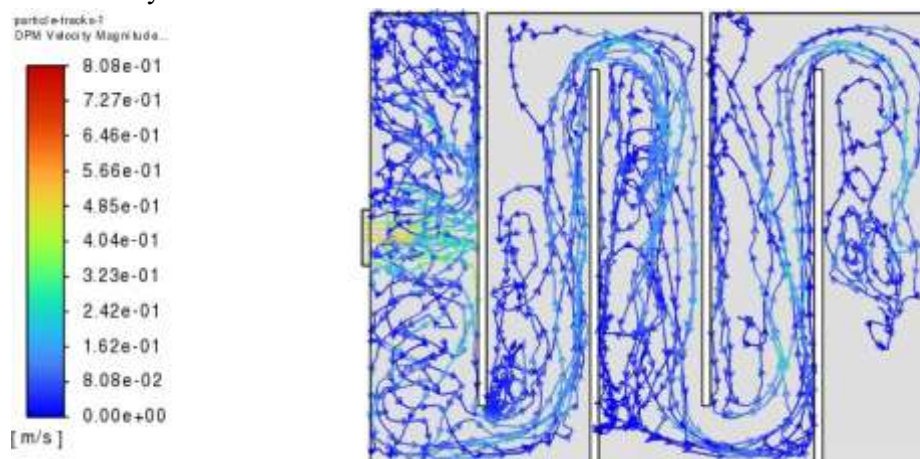


Figure 13. Air-filtration-Plants-zigzag-panels-v-.5-pm10-pathline-top view

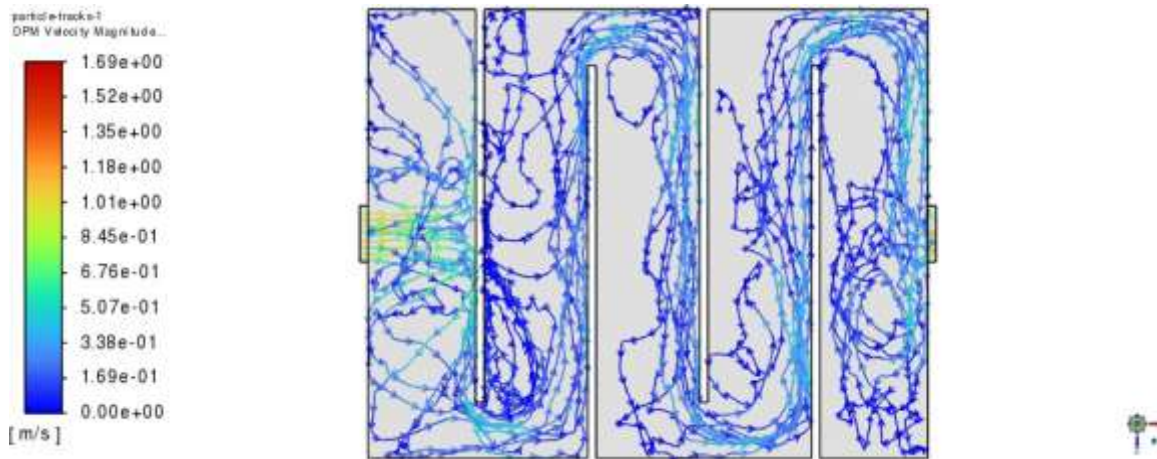


Figure 14.Air-filtration-Plants-zigzag-panels-v-1-pm10-pathline-top view

Figure 15 shows the zigzag panels at a velocity of 1 m/s, and it was gathered that an ample amount of deflection was noticed due to the staggered geometry of the panels. In these cases, it was realized that improved turbulence was obtained due to the enhanced mixing effect of dispersion of pollutants during filtration interaction.

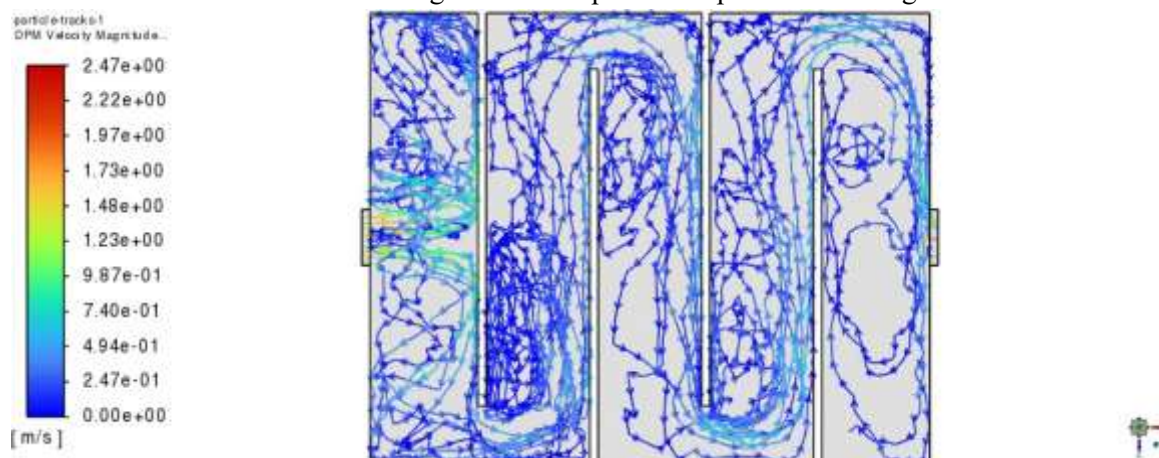


Figure 15.Air-filtration-Plants-zigzag-panels-v-1.5-pm10-pathline-top view

Figure 16 shows the zigzag panels at an inlet velocity of 1.5 m/s, and it was found that due to the zigzag pattern, greater intensity of vortex patterns was created, as well as more intense recirculation zones were generated as compared to the two other panels, namely blocking and parallel ones. It was also realized that due to continuous changes in directions, causes increment in the intensity of turbulence as well as in the characteristics of airflow.

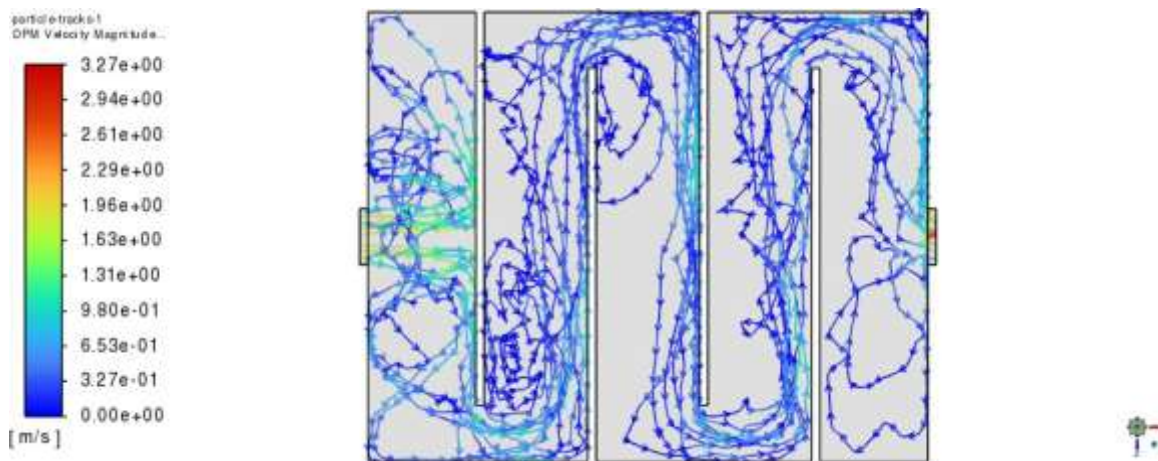


Figure 16. Air-filtration-Plants-zigzag-panels-v-2-pm10-pathline-top view

Figure 17 represents the zigzag panels at an air velocity of 2m/s and it was gathered that very complex patterns were realized. Besides this, turbulent eddies and recirculation zones were generated, which improved mixing of pollutants and increased the behavior of residence time, which proved better aerodynamic interaction between airflow and the vegetation of panels.

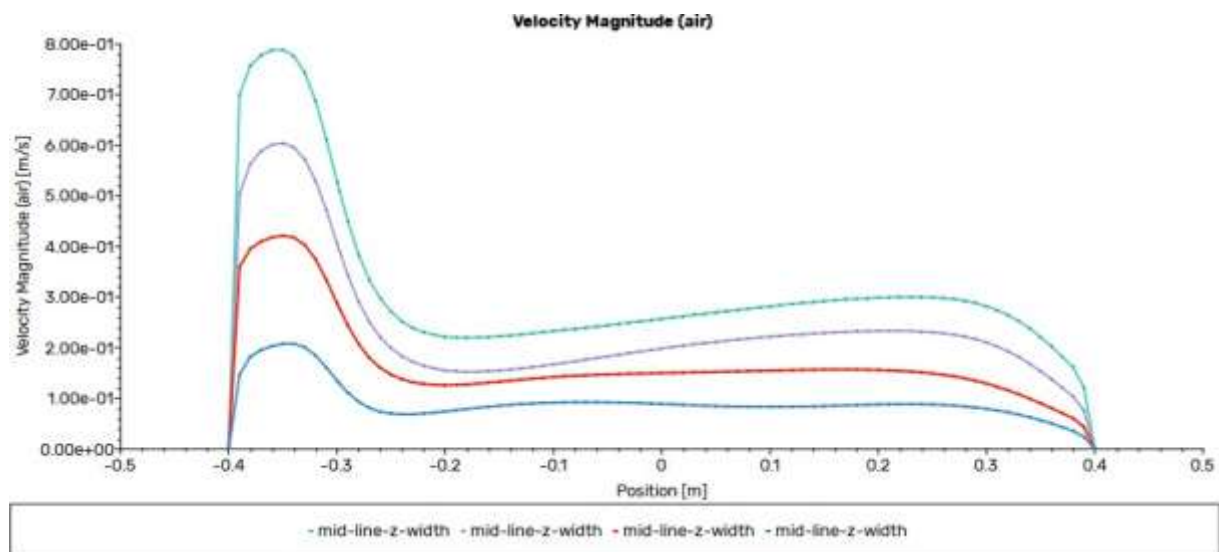


Figure 17. Air-filtration-Plants-zigzag-panels-v-.5-1-1.5-2-vel-graph-mid-line-z-width

Figure 18 shows the velocity profile of zigzag panels, and it was found through distribution of velocity shows considerable variations in velocities along the midline section owing to repeated changes in flow direction due to the zigzag geometry of panels.

3.4 Comparative Discussion

It was found in the present work that different types of plant panels have a significant effect on airflow and its related velocity. Besides this, different types of plant filtration panels have an effect on the mechanism of turbulence generation and the movement of pollutants through filtration zones. It was determined that, for the blocking panels' arrangement, maximum restriction was created, specifically reducing airflow at some locations. On the contrary, it was also found that for blocking panels, greater zones of distributed air were found behind the panels for high velocity cases. On the other hand, for the parallel panels, it was important to notice that airflow has become smooth via channels in a clear manner, which yielded pressure loss with smaller intensity with better flow patterns in terms of

consistency. In contrast to the other two panels, the third combination of panels, namely the zigzag pattern found to produce the greatest turbulence and enhanced mixing of air. Due to the geometry and arrangement of zigzag panels, the pollutants, including PM 10 particles, stay for a much greater time owing to continuous changes in air flow as well as in circulation effects. It was found that the zigzag panel outperforms the other two panels since, in this configuration, maximum contact happened between pollutants and air, which results in a better filtration effect via turbulence. It was gathered that a parallel configuration yields steady airflow with minimum resistance, while a blocking panel helps in capturing localized pollutants. Thus, it is important to realize that various types of panels help in the better design and layout of plant-based air filtration systems while maintaining airflow as well.

4. Conclusions

The current work deals with the CFD simulation to investigate the effect of the various types of plant panels on airflow as well as on pollutants spread in air filtration systems. Three different types of plant based filters namely blocking, parallel, and zigzag were utilized for studying the movement of PM10 particles at four different speed of air i.e., 0.5, 1.0, 1.5 and 2.0 m/s. On the basis of CFD simulation it was found that these types of layout of plant based panels have important role in determining airflow and filtration of pollutants. It was seen for the case of blocking panel, although the velocity of air has diminished considerably and at the same time pollutants were caught directly, but at the same time it causes generation of scattered zones of air were generated behind the panels usually encountered as higher velocities. Parallel configuration on the other hand offers less resistance and better consistent behaviour of airflow.

It is customary to note that the due to zigzag plant filter panels maximum phenomenon of mixing and turbulence were observed which causes pollutants to remain circulated with maximum interaction with panels. Again due to this reason, zigzag pattern found to be highly effective for increment in pollutant mixing and provides improved effect of filtration via turbulence which in turn has considerably increased particle contact with vegetation. Therefore due to these CFD investigations it was clear that for optimized air flow and pollution control through green filtration systems both shape and positioning of plant panels are quite important. Hence in this work a sustainable approach and energy efficient plant based filtration effect was demonstrated for cleaning purpose of urban air. The future work may include optimization and prediction of air pollution parameters using various machine learning techniques.

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