Research Paper

Geometrical Optimization of Closed-End Cylindrical Air Filter Using CFD Simulation

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Abstract: This research aims to evaluate the effect of porous filter configuration on flow characteristics within filter using CFD simulation. This simulation model was chosen for comprehensive analysis that considers different variables affecting the filter performances. Dynamics of the flow and pressure drop under different flow conditions and filter geometry were studied. The Euler-Lagrangian approach was used to model multiphase flow, and the standard K-ε model was used for turbulence characterisation. Particle size distribution was characterized using Rosin-Rammler distribution. The initial status of these properties was obtained by previous experimental references and their evolution over time was simulated at the cell level of the model using User-Defined Functions (UDF). The main conclusions of the study are: i) The pressure drop increased with flow rate and thickness of the filter but decreased with increasing filter length and diameter. ii) There is no significant change in velocity ratio with the distance from the filter inlet at the filter centre line except the first 5% from the inlet and last 5% close to the end. iii) it was identified that higher radial velocity ratios imply a less particle deposition within the filter media. The results also shows that the particle loading on 290 mm filter is 50% - 60% lower than the other filters but evenly distributed across the filter. However, the pressure drop decreased with the filter length. 55mm filter that has the highest radial velocity ratio performs poorly in particle trapping.

Keywords: CFD, Porous Media, Filtration, Particle Deposition, Pressure Drop, UDF

The Korean text of this paper can be translated into multiple languages on the website of http://jksee.or.kr through Google Translator.
1. Introduction

Many industrial processes produce gases that contain solid particles/liquid droplets or gaseous pollutants that are considered harmful. These particulate emissions must be removed from the airflow before it is released into the environment. Different criteria and policies have been introduced by regulatory bodies that all these industries must adhere to by maintaining proper mechanisms for air purification and process implementations. This has made significant potential for developing emission gas cleaning technologies worldwide.\(^\text{1}\)

A rigid, closed-end, cylindrical filter is one such technology currently used in both normal air filtration (with fibrous filter media) and warm air filtration (with ceramic filter media) processes. The improved air filtration performances of this type of filter depend on both the physical properties of the filter media and gas flow dynamics across the filter. Previous studies reveal that flow pressure and velocity properties across the filter axes and filtration surfaces are much more complex with non-uniformities. This unevenness results in diminishing filtration performance and durability.\(^\text{2}\)

Numerous studies have been carried out in recent years regarding fibrous air filters.\(^\text{3-5}\) Most of these studies have focused on microscale models of fibrous media to study their behaviours. However, plenty of research has considered the macromodel behaviour of the overall filtration process and very less of them are about cylindrical, fibrous filters.\(^\text{6-8}\)

Physical properties of the filter including filter length, diameter, thickness of filtration material layers, porosity, permeability, and inertial resistance of the filtration material were identified as affecting filter performance. The main objective of this study is to reveal the influence of these factors using CFD analytical methods and experimental data obtained from previous research. ANSYS FLUENT was employed as the primary CFD simulation software tool in this study. The overall CFD analysis was based on a customised simulation model which was validated by comparing its results with previous research, including laboratory testing conducted in an actual industrial environment.\(^\text{8}\) This verification process proved valuable in saving unnecessary time and resources that would have been spent on replicating the same experiments. Furthermore, the implemented simulation model was utilized to investigate a wide range of variables affecting performance.

This analysis was performed considering mixed/contaminant flow of air with solid/oil aerosol particles to assess the effect of physical variables of the filter on flow characteristics and pressure variation across the filter. The Discrete Phase Model (DPM) in Fluent was employed to study the characteristics of mixed flow using the Euler-Lagrangian reference frame. However, the study of mixed flow is not straightforward, as the deposition of solid and aerosol particles on the porous media has a significant effect on its characteristics (permeability and inertial resistance) over time. This phenomenon has been investigated by previous researchers.\(^\text{7-9}\)

The effect of particle deposition was incorporated into the simulation model using the User Defined Functions (UDF) to customize the software. All UDFs were written with extensive care to replicate the actual conditions and run effectively. This type of simulation demands high memory capacity and longer calculation times, particularly on well-performing computers. The simulation was conducted with four different filter lengths, flow rates, internal diameters, and filter thicknesses.

This study is conducted as an extension to the study by\(^\text{8}\) with significant improvements. While the previous research concentrated on implementing an economically viable CFD model to forecast the flow behaviour of a specific cylindrical filter, this study extends the investigation to analyse the impact of various porous filter configurations (cylindrical) on pressure and velocity characteristics. By leveraging the same conceptual framework, this research aims to not only identify but also compare the influence of different filter arrangements on fluid flow characteristics. Basic model parameters were assigned to be identical to the previous study to validate the model with its experimental results. UDFs used in this study were simplified compared to the previous study such that to utilise Ansys Fluent inbuild functions (particle injection, drag force etc) at a maximum level rather than assigning external calculations by the UDF that consumes more time and computational resources. This was a necessary requirement since there were multiple models to be simulated within limited time with minimum resources. Same UDF was used for all different simulation models.

2. Governing Theories in the Simulation Model

There are four fundamental concepts associated with the study of the filtration process across porous media. These include modelling of the effect of the porous zone on the flow characteristics, modelling of particle motion, model of particle distribution, and the examination of the impact of particle deposition on the filter media. ANSYS FLUENT 2023 R2 is
utilized as the basic CFD modelling software that offers a range of options for integrating these elements into the simulation model. The governing theories underlying these models and their respective variables have been further discussed in the following sections.

2.1. Model of the Porous Zone

In ANSYS FLUENT, porous media has been defined as nothing more than an extra momentum sink to the governing momentum equations. This additional momentum source term for a multiphase flow system has been defined in the governing momentum equations as equation (1),

$$ S_i = - \left( \sum_{j=1}^{3} D_{ij} \mu v_j + \sum_{j=1}^{3} C_{ij} \frac{1}{2} \rho |v|_j \right) $$

These two parts represent the viscous loss term and the inertial loss terms, respectively. It has further been simplified for a case of simple homogeneous porous media in ith direction as equation (2),

$$ S_i = - \left( \frac{\mu}{\alpha} v_i + C_2 \frac{1}{2} \rho |v|_i \right) $$

The porous cell zone of the filter has been defined in the software incorporating parameters such as viscous resistance (inverse of the permeability, \( \alpha \)), inertial resistance (\( C_2 \)) and porosity (\( \epsilon \)). Initial values for these properties by considering a clean filter media was obtained to imitate the model by referencing their experimental results.

These values are applicable as constants only for simple homogeneous air flow across the porous media. They were further considered as initial conditions while using UDF for particle deposition in the filter. However, in the FLUENT simulation model, no effect of porosity value was observed on the governing momentum equations at steady state. Consequently, there is no observable impact on pressure and velocity distributions in cases where the flow remains homogeneous.

2.2. Discrete Phase Model

Main purpose of this study is to evaluate the filtration performances that involves inert particles mixed with an air flow which has definite initial velocity/pressure based on their application. To simulate particle characteristics in ANSYS FLUENT, the discrete phase model was used which is governed by following sets of equations written in Lagrangian Reference Frame that determines the tracks of discrete phase particles by balancing forces acting on them:

$$ \frac{dv_i}{dt} = F_D(v_i - v_p) + \frac{g_i(\rho_p - \rho)}{\rho_p} + F_i $$

\( F_D(v_i - v_p) \) represents the drag force per unit particle mass in ith (x, y or z) direction such that,

$$ F_D = \frac{18 \mu}{\rho_p d_p^2} \cdot \frac{C_D Re}{24} $$

Reynolds number was defined as:

$$ Re = \frac{\rho d_p |v_p - v_i|}{\mu} $$

Where \( F_i \) in equation (3) represents all additional forces in ith direction under any special circumstances. \( F_i \) should be substituted with the source term defined in equation (2). For a low volume fractions of discrete particles, all single particles can be tracked separately. When it becomes quite a larger fraction, the option of “parcels” has been used to minimize the time and calculation resources consumed for single particle tracking in the simulation.

Drag Coefficient (\( C_D \)) has been defined in the Euler-Lagrange model under several laws. Spherical Drag Law is one of the most used laws that has been defined with constants that is applicable over different ranges of Reynold numbers by. The Spherical Drag Law is given as:

$$ C_D = a_1 + \frac{a_2}{Re} + \frac{a_3}{Re^2} $$

Discrete Phase Model (DPM) is highly regarded for simulating cylindrical filter performance in FLUENT’s due to its advanced capabilities such as detailed tracking of individual particles and
accommodating different particle sizes, densities, and shapes encountered in the filtration processes. The DPM’s validation against experimental data enhances reliability, while its customizable parameters and boundary conditions ensure simulations closely match real-world scenarios. Robust post-processing tools further facilitate visualization and analysis of particle trajectories and concentration profiles, making DPM model an optimal choice for comprehensive performance simulations of these types of filters.

2.3. Modelling of Particle Distribution

Different models have been developed to describe dispersed systems like fine particles. These models are useful in obtaining the overall particle distribution in a short period without waiting for long time-consuming sedimentation methods. In this application, the aerosol sample includes droplets of different range of diameters. The Rosin-Rammler size distribution is one of such well-known methods that is commonly used in many industries. The experimental observations obtained by have revealed that aerosol samples closely fulfill the relationship of R-R distribution. ANSYS FLUENT has provided the option of R-R distribution model in discrete-phase spray modelling. Particle distribution can be defined by providing the minimum, maximum, and average particle size with size distribution parameter.

\[ Y_d = e^{-\left(\frac{d}{d_0}\right)^n} \]  

\( Y_d \) in this expression is defined as the mass fraction of particles greater than \( d \). The average particle diameter (\( d_0 \)) and spread parameter (\( n \)) have been calculated as 1.9 \( \mu m \) and 2.45 respectively for the R-R distribution.

Basha et al. experimented with special equipment to measure aerosol particle distribution related to their case study. The same distribution parameter has been used in this experiment since the initial filter properties were also obtained by referring to the same study.

Different flow rates have been used in this study that consist of same particle distribution.

2.4. Defining Porous Zone with UDF

The effect of particle deposition on inertial and viscous resistance of a porous media has been published by based on their studies. The original resistance values of a clean filter are increased by a factor of mass deposited to the total mass in each cell. deposited mass fraction is defined as,

\[ m_{pf} = \frac{m_{pd}}{m_{fluid} + m_{pd}} \]  

\( m_{fluid} \) stands for air mass in the cell and \( m_{pd} \) represents the deposited particle mass.

\[ \frac{1}{\alpha} = \frac{1}{\alpha_0} \left(1 + m_{pf}\right) \]  

\[ C_2 = C_{20} \left(1 + m_{pf}\right) \]

Deposited particle mass is calculated at the end of each time step and this values to be stored in a User Defined Memory (UDM) to use cumulatively in the future time steps.

These UDMs are created for each cell and gets updated at each time steps by demanding huge memory capacity to save the data for a longer transient period. However, by using particle parcel method and defining property changes only for designated cell zones within the UDF, this overuse of memory can be minimized. Flow chart of running UDF in the simulation is given in Figure 2.

2.5. Scope of the Study

This analysis has been based on CFD simulations with ANSYS FLUENT which can be evaluated with different variables rather than laboratory/industrial experiments that consume time and resources. Therefore, the following scope of work has been followed (Table 1) to represent all the possible filter configurations such as different filter dimensions and flow rates.

![Flow Chart of Running UDF in the Simulation.](image-url)
All these simulations are based on one model that was developed by following a critical study and validated with previous experimental results. The specifications of the experimentally validated simulation model are given in Table 2 and the filter geometry is presented in Figure 3.

A basic simulation model was used for validation with experimental results. Dimensions and operating conditions for this model was imitated from research by as follows.

3. Results and Discussion

3.1. Validation of Basic Simulation Model - Aerosol Mixed Flow

The results obtained from the basic simulation model agree to a higher degree with the experimental results. The choice to validate the model using pressure drop was made because it is a key variable in the study of flow in porous media. Additionally, measuring pressure difference is simpler compared to other variables like velocity or particle concentration. Figure 5 presents the comparison of experimental data and presents simulation results. This variance indicates a linear pressure drop after a certain time of settling down the system. However, there is still a difference between the experimental and simulation results. This difference is 3% to 16% for a 20 CMH airflow.

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| Table 2. Specification of Experimentally Validated Simulation Model. |
|--------------------------|-----------------|-----------------|-----------------|-----------------|
| Variable of study        | Value 1         | Value 2         | Value 3         | Value 4         |
| Length                   | 210 mm          | 250 mm          | 290 mm          | 330 mm          |
| Flow Rate (Normal)       | 20 CMH           | 30 CMH           | 40 CMH           | 50 CMH           |
| Internal Diameter        | 45 mm            | 50 mm            | 55 mm            | 60 mm            |
| Filter Thickness         | 10 mm            | 12 mm            | 14 mm            | 16 mm            |
| Constant Characteristics |                 |                 |                 |                 |
| Length (40 CMH)          |                 |                 |                 |                 |
| Diameter (45 mm)         |                 |                 |                 |                 |
| Filter Thickness (10 mm) |                 |                 |                 |                 |

Fig. 3. Filter geometry.

Fig. 4. Mesh of the porous zone.

Fig. 5. Comparison of experimental and simulation results.
rate and to 13% to 17% for a 40 CMH airflow rate in the first 10 minutes.

This difference can be expected due to the assumption made in the simulation model which assumes that all particles moving across the filter are deposited within the porous media. This assumption was incorporated into the model by assigning a User Defined Memory (UDM) that updates cumulatively at each time step. In the actual scenario, it is not realistic to expect 100% particle deposition. Therefore, experimental pressure drop results are quite lower than the simulation results in the first 10 minutes of the simulation. With a higher airflow rate, the particle drag force increases, and particles tend to leave the filter media more easily. This explains the reason behind the 20CMH airflow rate having less pressure drop deviation than the 40CMH airflow rate. Simulation results indicate the pressure drop after 1\textsuperscript{st} simulation time step (0.05s).

This simulation model can be further developed to incorporate actual particle deposition theories to reduce the deviation in results by the current assumptions. However, that type of model will require extensive computational resources with a longer time which would act counter to the core objective of this study, which is to develop a sustainable method of analysis.

Therefore, this simulation model was used to examine all the subcases to evaluate the filter performance while acknowledging the expected deviations in results.

3.2. Graphical Representation of Results

In this model, all particles move across the filter and some exit based on the drag forces acting on them. However, particle mass moving across each cell is stored in a UDM by assuming all particles are trapped in the filter. Using UDMs is much more convenient for the simulation to reduce time and consume computational resources rather than calculating each particle motion at all the time steps that will increase gradually. For demonstrational purposes, only a specific case (210 mm filter with 40 CMH flow) has been selected under this section to provide figures of deposition patterns.

Particle deposition and motion in the simulation are clearly shown in Figure 6 on a random cross-section of the filter. Figure 7 above shows the particle distribution in different layers of the filter.

The maximum deposition of particles is at the middle layers

![Particle concentration on a cross-section (after 2 mins).](image1)

![Particle distribution pattern at different layers of the filter (after 2 mins).](image2)

![Particle Concentration at Cross Sections Across Axis (after 2 mins).](image3)
of the porous zone while internal and external layers have minimum particle deposition. Particle loading contours in Figures 6 and 7 above clearly demonstrate that particles are deposited in the forms of strips along the filter that are nearly circular.

On the other hand, particle flow is moving across the filter in a specific path rather than moving across the whole filter area. This localized deposition shows that flow across a porous zone chooses a path having minimum resistance when the particle loading increases at some locations.

Figure 8 provides a clearer idea about the distribution of flow paths that need to be studied in conjunction with Figures 6 and 7.

Pressure drop across a new/clean filter depends on the porous media characteristics, flow characteristics and particle deposition characteristics. Figure 7 indicates how the pressure drop varies with time at the first few minutes of starting filtration process. Within a couple of minutes, the pressure drop increased drastically due to fast change in the flow structure from one stream to small streams within the filter media zone until to find preferential path. This generate a high turbulence which is reduced with time and the flow becomes laminar flow.

3.3. Results Analysis for Different Filter Configurations - Aerosol Mixed Flow

3.3.1. Impact of air flow rate on the filter performance

Air is the media that transports the particles across the filter. Therefore, the flow rate is highly impacting the performance of the filter. Figure 10 indicates that high flow rates create a higher pressure drop. When consider the curve shape, higher flow rates have steep curvature at the beginning that indicates the high rates of particle deposition compared to the lower flow rates.

In the study conducted by [13], it was observed that the pressure drop across a closed-end cylindrical filter should exhibit a linear
relationship with the flow rate. Figure 11 depicts a linear trend with minor deviation at higher flow rates. This discrepancy can be attributed to the assumption of 100% particle deposition within the simulation model which implies more particle deposition and high-pressure drop than the actual values.

Figure 12 provides a clear representation of the radial velocity ratio (radial velocity at the filter centre line/inlet velocity) at the filter centre line. As the filter length is not changed, the curve shape is almost alike for each flow rate. However, higher flow rates induce the highest radial velocity.

Radial flow velocity is one of the most important parameters that can be used to identify the trend of particle trapping within the filter media. Radial velocity at the filter axis has the least value and get increased while moving towards the filter internal wall. Near the wall, this velocity becomes unstable because of particle deposited within filter media. This variation has been demonstrated in Figure 12(b).

When considering the particle concentration within the filter media in Figure 13, the lowest flow rate indicates a most even distribution along the filter length rather than higher flow rates. The trend line of the concentration pattern is almost horizontal. For the highest flow rate value, the maximum particle concentration value has been limited to 0.0008 kg. It seems like the highest flow rates induced less trapping of particles compared to the other lower flow rates. This phenomenon has been identified by other researchers because of increased collision between particles that provide an external push on the particles to leave the porous zone. Increased drag force on the particles at higher flow rates can be identified as the

![Fig. 14. Pressure drop with time for different filter length.](image1)

![Fig. 15. Pressure drop variation with filter length increment (at different times).](image2)
other reason behind this (Equation 4).

The results shown in Figure 13 are useful in identifying the particle distribution trends along the filter. However, these particle loading patterns do not indicate any proper order because these results were obtained considering only a random plane across the filter. As discussed in Figures 6, 7 and 8 these localized particle deposition patterns are not evenly distributed around the filter body.

3.3.2. Impact of Filter Length on the Filter Performance

The simulation results presented in Figure 14 indicate that varying the filter length has a significant impact on the pressure drop. Increasing the filter length by 19% to 57% results in a reduction in the pressure drop ranging from 22% to 48%. This observed variation can be attributed to the diminishing rate of change as the length increases, as depicted in Figure 15, where pressure drop follows a power function of length. This pattern remains consistent even when using different time steps.

It leads to the stabilization of the velocity ratio in Figure 16, particularly in the central region along the filter axis. Conversely, when the filter length increases, the closed end of the filter appears to have a more pronounced impact on disturbing the flow field. This phenomenon suggests that particle concentration at the end of the filter becomes higher as it can be observed in Figure 17. Notably, the slope of the trendlines for particle deposition (loading) exhibits a similar pattern for both the 290 mm and 330 mm filters, resulting in near overlap on the radial velocity ratio diagram above. Particle loading on 290 mm filter is 50% - 60% lower than that of other filters but evenly distributed across the filter. The highest radial velocity ratio has induced this lowest particle concentration. This further indicates that the filter with 290 mm length lack of performance in particle trapping within the filter media.

3.3.3. Impact of Filter Diameter on the Filter Performance

The results from Figure 18 highlight the notable influence of altering the filter diameter on the pressure drop. An increase in filter diameter by 11% to 33% leads to a corresponding reduction in the pressure drop, ranging from 12% to 28%.

This observed trend can be attributed to the decreasing rate of change as the diameter increases, which is graphically represented in Figure 19 where it becomes evident that the pressure drop nearly follows a power function in relation to the diameter. Remarkably, this consistent pattern continues across various time steps.

The alteration of the filter's internal diameter has a clear effect
on the radial velocity ratio. However, this distribution exhibits a consistent pattern for all diameters, maintaining a flattened and nearly constant variation along the middle section of the filter axis, as illustrated in Figure 20. Notably, the increase in radial velocity ratio does not demonstrate a proportional relationship with the diameter. Surprisingly, the 55 mm filter exhibits the highest velocity ratio despite the order of magnitude of the diameter.

Figure 21 shows that filters with 50 mm and 55 mm diameters indicating almost even particle loading across the filter while 45 mm and 60 mm filters still show a peak at the mid-sections. 55 mm filter that has the highest radial velocity ratio induced the least particle concentration along the filter. It further implies that filter with 55 mm diameter not perform well in particle trapping compared to the other diameters.

3.3.4. Impact of Filter Thickness on the Filter Performance

The simulation results depicted in Figure 22 demonstrate a notable influence of altering the filter thickness on the pressure drop. As the filter thickness increases by 20% to 60%, there is a corresponding rise in the pressure drop, ranging from 15% to 40%.
The increase in pressure drop shows an almost linear relationship with the filter thickness, as demonstrated in Figure 23. However, when examining the radial velocity ratio, there is no considerable variation observed across different thicknesses; all lines coincide with each other in Figure 24. This suggests that the flow field maintains consistent velocity characteristics, in contrast to the varying static pressure differences across the filter media.

Higher thickness of filter implies high resistance on the air flow resulting in comparatively less particle loading after a definite running time. This is clearly indicated by the particle loading diagram in Figure 25. As the radial velocity ratio for all different filter thicknesses are same (Figure 24), the variation of particle distribution cannot be described by referring to the radial velocity ratios. It totally depends on the resistance induced by the porous media.

4. Conclusion

This research aims to evaluate the performances of cylindrical...
moulded filters to reduce the repetitive experimental study for each new product. CFD model has been developed and validated using previous experimental data. Then, the model was used for simulation to study the various variables influencing the filter performance. The main conclusions from the present study can be summarised as:

- The simulation model was validated using pressure drop across the filter because it a key variable in the study of flow in porous media. Additionally, measuring pressure difference is simpler compared to other variables like velocity or particle concentration.
- The use of a well-defined simulation model to study the behaviours of closed-end air filters was a successful method since it allowed to widen the scope of the study. However, this type of complex CFD simulation requires high computational power and running time to obtain a small piece of timestep results. The reduction of simulation time should be separately studied using machine learning techniques rather than increasing computational resources such as parallel processors, RAM capacity, remote supercomputers etc.
- Basic parameters that were identified as severely impacting the filter performance were studied in this research. While changing one parameter, all other parameters were kept constant to reduce the number of different combinations. There were a lot of important observations obtained from the study.
- While studying different air flow rates, filter lengths, and internal diameter of the filter vs the particle deposition, it was identified that higher radial velocity ratios imply a less particle deposition within the filter media.
- Most importantly, the increment of filter characteristics demonstrated radial velocity ratio with humped deviation that was not proportionally deviated. For different filter lengths from 210 mm to 330 mm, the maximum velocity ratio was at 290 mm and for different internal diameters from 45 mm to 60 mm, the maximum velocity ratio was at 55 mm. This further implies that filter characteristics have non-optimal values that need to be avoided.
- when considering different filter thicknesses, the radial velocity ratios become similar for all thicknesses. Therefore, the particle deposition should be described with the porous media resistance rather than the velocity values. on the other hand, the radial velocity was identified as affected only by the flow rate, filter length and internal diameter, not the filter thickness.

- The simulation model was validated using previous experimental results and it was identified as having a minor error for high flow rates. However, this error kept constant with time for 40CMH, and this flow rate was used as a constant for all other sub-cases. Therefore, the simulation results obtained for all cases will be considered as carrying the same error percentage as shown in section 3.1. However the results can be directly used to identify the variation patterns rather than obtaining actual values.
- Graphs obtained for pressure drop variation with time are one of the most useful results obtained from the study since the trendline equation of each of these plots can be used to predict the filter lifetime to reach the expected pressure drop. These equations are in the following form.

\[
\Delta p = a \ln(t) + p
\]  

(11)

In this equation, \( p \) represents the initial pressure drop of the clean filter. \( a \) is a model-specific constant, which depends on all the parameters. \( \Delta p \) and \( t \) represents the pressure drop and time, respectively.

- This study carries significant environmental implications such as the potential to improve filter efficiency, leading to reduced energy consumption of equipment during operation with the filter and minimizing the environmental impacts associated with frequent filter replacements and manufacturing. Enhanced filtration efficiency also contributes to better air quality by effectively trapping aerosol pollutants, thereby promoting healthier indoor and outdoor environments.

**Nomenclature**

- \( F_i \): Model dependent Source term
- \( g \): Gravity (m/s²)
- \( v \): Fluid velocity (m/s)
- \( \mu \): Viscosity
- \( \rho \): Fluid density (kg/m³)
- \( p \): Static Pressure (Pa)
- \( s_i \): Source term
- \( C, D \): Prescribed metrics
- \( v_p \): Particle velocity zd/s
- \( \rho_p \): Particle density (kg/m³)
- \( d_p \): Particle diameter (m)
- \( Re \): Relative Reynolds Number
- \( C_D \): Drag coefficient
- \( k \): Permeability
a_0 \quad \text{Initial value of permeability}

C_2 \quad \text{Inertial resistance}

C_d \quad \text{Initial value of inertial resistance}

d \quad \text{Particle diameter (m)}

\bar{d} \quad \text{Average particle diameter (m)}

n \quad \text{Size distribution parameter}

m_{pf} \quad \text{Particle deposition mass factor}

m_{pd} \quad \text{Deposited mass of particle}

\Delta n \quad \text{Porous media thickness}

\varepsilon \quad \text{Porosity}

References


Declaration of Competing Interest

The authors declare that they have no known competing interests or personal relationships that could have appeared to influence the work reported in this paper.

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