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Validating Filtration Efficiency of Nonwoven Air Filters through CFD Analysis

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***Abstract*— This paper presents a computational study utilizing Computational Fluid Dynamics (CFD) to assess and validate the dust filtration efficiency of nonwoven fabric-based air filters. The methodology involves the creation of a detailed 3D model of the filter structure including the filter fabric. The nonwoven fabric samples designed using polypropylene and polyester are analysed in this work. A high-quality mesh is generated to accurately capture the flow behaviour within the computational domain. Boundary conditions are meticulously defined to simulate real-world operating conditions, including inlet airflow velocity and outlet pressure. A microstructure filtration model is implemented to simulate the capture mechanisms of particles by the filter media. The CFD simulation is utilized with appropriate solver settings, and post-processing techniques are employed to analyse critical performance metrics such as pressure drop, airflow distribution, and particle capture efficiency. Validation of the computational model is conducted by comparing simulation results with experimental data, establishing the accuracy and reliability of the numerical approach. Very good agreement was found between the experimental and simulated filtration efficiency.**

***Index Terms*— nonwoven fabric, air filtration, image processing, porosity, capture efficiency, fluid dynamics**

I. Introduction

The presence of particulate matter (PM) in the atmosphere poses significant health risks, leading to respiratory diseases among humans[1, 2]. At the same time, industries such as electronics, medical treatment, and biology require environments with high cleanliness standards. Globally, strict rules governing particulate matter emissions are being set in response to growing environmental concerns. Air filters play a crucial role in maintaining air quality by removing pollutants, allergens, and particulate matter from the air we breathe. Standards for air filters set by some industries emphasize how important it is to monitor filter functioning. These standards state that dust collection causes resistance to rise to a predetermined "final resistance," marking the end of the filter's useful life. Fibrous filters specially designed using nonwoven textiles have excellent performance in the field of dust particle filtration due to their versatility, durability and cost. The performance of such filters is evaluated in terms of

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filtration efficiency. Understanding the relationship between filtration efficiency and pressure drop in fiber filters is crucial for reducing energy consumption, optimizing filtration processes, and extending their service life. By leveraging computational simulations, engineers can efficiently analyze these key performance metrics.

The use of computer technology to recreate fiber filters in three dimensions and study their filtering efficiency under dust loading through Computational Fluid Dynamics (CFD) has been increasingly popular in the last few decades[3-5]. Nazarboland et al. used CFD to simulate the particle deposition of particles, of varying shapes like oval, flat, spherical, and needle, respectively[6]. Computational fluid dynamics (CFD) and discrete element method (DEM) or discrete-phase model are commonly employed to correctly quantify the continuous motion properties of fluid and the interaction between particles and solid phase [7],[8]. Li et al.[9] applied the Discrete Element Method (DEM) to investigate the formation of dendritic structures on single fibers. Concerning fibrous media. In general, there are two types of micro-scale models of fiber filters: those with a single fiber and those with fibrous media. Hosseini et al. utilized a user-defined function (UDF) to augment the standard discrete phase model (DPM) module of the ANSYS software for aerosol filtration modelling, achieving visualization of particle deposition on single fiber surfaces[10]. Other researchers[11], [12] employed the Lattice-Boltzmann method (LB) to numerically simulate the deposition morphology on single fibers, subsequently examining the impact of deposited particles on filtration efficiency and pressure drop. Saleh et al. combined C++ subroutines with ANSYS CFD code to simulate the pressure and filtration efficiency in the case of particle loading. Their work analysed the influence of dust loading on pressure drop and filtration efficiency under various Solid Volume Fractions (SVFs) of fibrous media. They stated that the three-dimensional (3-D) microscale had a brighter future because of the high-speed development of computers as compared to simulation methods of the 1-D macroscale models. The OpenFOAM tool was used by Shu et al. [13] to study the filtration and deposition of dust properties of fibrous media based on a 3-D model of multilayer fibrous media using the Eulerian-Lagrangian framework. The use of fibrous material in simulating fiber filtration equipment through Computational Fluid Dynamics (CFD) models offers cost-effectiveness but overlooks microstructure features, consequently failing to accurately capture particle behaviour and pressure drop calculation, thereby impacting flow distribution. To effectively simulate gas-solid two-phase flow, three critical aspects must be addressed: the accurate representation of particle trapping, dynamic changes in pressure drop during dust loading, and the estimation of filtration indices such as filter efficiency. Some researchers have devised a calculating approach for fibrous media during dust loading based on CFD porous medium, which takes into account the features of surface filtration. Because DPM uses a greater time step and less stored information than DEM, it has the advantage of quick computations and lower computer resource requirements[14]. Saleh et al. [15] calculated the link between pressure drop and dust deposition after performing a numerical simulation on the particle deposition characteristics of fiber filters based on porous media. When the particles accumulate in the filter screen, the pressure drop of the fluid phase will occur across the filter media boundary[16, 17]. A novel technique for the microstructure model of dust deposition with arbitrary forms and multi-dispersed particles was created by Yousefi et al. [18]. This suggests that the fibrous filter material for dusty air filtration may be accurately evaluated using CFD. This study investigates the filtration efficiency and pressure drop over nonwoven fabric-based filters using CFD.

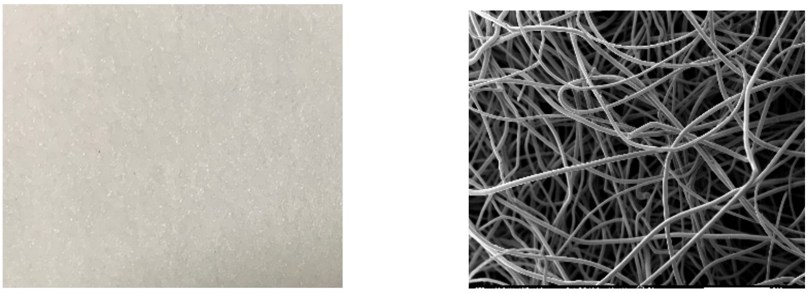
The steps taken by this study are: First of all, the flow field in the fibrous media was assessed via real-time experimentation for the nonwoven filter, secondly a Lagrangian-based discrete phase model (DPM) was established using the k-ω model and the user-defined functions in ANSYS-Fluent and trapping and loading of particles in the CFD porous media were understood. The filtration efficacy and pressure change were estimated for particle sizes in the range of 10-100 microns.

II. Materials And Methods

The nonwoven fabric is the main part of the filtration process. It was procured from the locally established nonwoven industry. The constituents used to design the fabric are Polyester and polypropylene with varying percentages. Six such samples with varying areal weights and fiber mixture of nonwoven fabric were acquired from the industry. All the samples were then tested in the laboratory as per the test standards set by the American Society for Testing and Materials (ASTM) [19] [20]. The fabric sample weight, thickness of the fabric, air permeability, pore size, and porosity were measured using test procedures in the textile laboratory. The fabric image of sample no. 1 taken by the camera and its SEM (Scanning electron microscope) micrograph is shown in Fig 1.

A. Filtration Experimentation Through Nonwoven Filter Media

For a real-time assessment of filtration performance, a specially designed filtration test rig was used to determine the filtration efficiency of every fabric sample. The airflow in this experiment was mixed with standard dust particles of 10-100 microns weighing 2 grams. The dust plus air flow was passed through the filter and was evaluated for various flow rates like 40 CFM, 50 CFM and 60 CFM. The pressure drops were also marked at each trial. The experimental values of measured parameters for all samples are given in Table I.



(a) (b)

Fig. 1. Real image (a) and SEM micrograph (b) of a nonwoven fabric sample

TABLE I: NONWOVEN FABRIC'S MEASURED PARAMETERS

Sample No.	Density Of Fiber gm/Cm^3	Fabric Weight gm/m^2	Fabric Thickness mm	Fiber Diameter in um	Porosity	Filtration Efficiency (%)
1	1.155	200	3.217	19.17	0.944	54.99
2	1.38	160	2.73	17.54	0.958	47.7
3	1.38	200	3.335	26.16	0.953	45
4	0.93	200	3.39	26.16	0.937	62.5
5	1.155	160	2.95	23.48	0.956	57
6	1.38	120	2.175	21.47	0.960	23.73

B. Filtration Simulation Through Fibrous Media in CFD

Aerosol mixture filtering is not the same as filtering just liquid or only solid aerosols. Interactions between particles in the case of simultaneous filtration of solid particles lead to changes in the filter structure that have a significant impact on filter efficiency [21, 22]. CFD simulations are based on fundamental conservation laws of mass, momentum and energy [23]. These laws are expressed by partial differential equations whose boundary conditions are defined by the computational geometry in CFD simulation tools. ANSYS is a general-purpose finite element analysis software primarily used in the mechanical or Multiphysics domain. ANSYS Fluent is mostly preferred module of ANSYS to analyse the filtration performance of microstructures. For the current work, the filtration behaviour was tested using the ANSYS @2020 tool. The steps used are described below.

1) Geometry of Filter Media and Boundary Conditions

ANSYS Design Modeler® was used to create the model for the current study. The first step is to create the two-dimensional geometry of the filter test rig with dimensions of 3.3-inch diameter and 29 inches in length as shown in Fig. 2. The filter fabric was placed inside a test rig as a porous media. The filter dimensions and physical characteristics of the fabric filter such as thickness and porosity were applied to the porous zone. The domain was discretized by mesh approach. Meshing was applied to the entire model and a mesh consisting of 9432 elements was selected according to grid independence study. The resulting meshed structure is depicted in Fig. 3 with rectangular elements.

Fig. 2. Geometry of filter test rig

The boundaries were stated as ‘inlet’, and ‘outlet’, for the entire geometry and interiror_Filter_in and interiror_Filter_out_ for the fabric porous zone. The air is blown from the inlet wall along with dust and escapes from the outlet side.

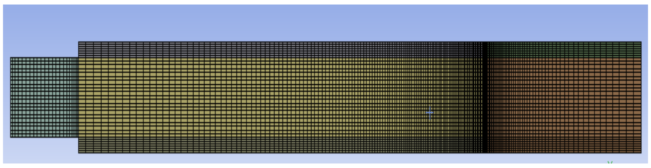


Fig. 3. Meshing view

2) Governing Equations

For fluid flow, fundamental equations of continuity momentum and energy equations were considered in CFD[24]. Along with this for a homogeneous porous media, a standard source term can be expressed as,

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

Where α is permeability, C2 is the inertial resistance factor, ρ and v are fluid density and velocity. The first term on the right-hand side of the equations represents the viscous loss term and the second term represents the inertial loss term. The gas through the fibrous media is laminar flow, so the pressure drop of fibrous media follows Darcy’s law. The pressure drop calculated by the CFD tool in each of the three (X, Y, Z) coordinate directions within the porous region I given as,

$$\Delta p_x = \sum_{(j-1)}^{3} \left(\frac{u}{\alpha_{xj}} v_j \, \Delta n_x\right) \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where Δnx is the actual thickness of the porous region in the model and υj is flow velocity. αxj is the permeability (porosity).

3) Solver Settings for Computation Domain

The proposed work was designed for air filtration for which multiphase modelling was selected in ANSYS-Fluent workbench. The Eulerian dense discrete phase model (DPM) is an appropriate model for this flow simulation. The air material properties such as density and velocity were set. In viscous model was set to laminar flow. Dust particles in the range of 10-100 um mixed with air were treated as injectors in the DPM model. In the injector setting in ANSYS, the diameters of these particles were set in 0.01 to 0.1 mm which were passed through the inlet wall of the filter test geometry in normal direction. The density of these particles was set in injector material properties. Boundary conditions were set for air at the inlet and dust particles for the outlet. Due to the limitation of ANSYS to set particle size in micrometer the DPM of ANSYS was updated by a UDF function to load the various particle sizes at various time steps. The fabric part was a porous zone in this work. The porous zone properties such as inertial resistance, C2, and viscous resistance are obtained from the pressure-velocity curve indicated by the quadratic equation given by equation 1. Experimental data that was available in the form of pressure drop against velocity through the porous media, was extrapolated to determine the coefficients for the porous media. From the pressure drop-velocity curve, a second-order equation was derived as given by equation 3. From its coefficients, the values of the inertial resistance, C2, and viscous resistance $1/\alpha$ were calculated using the equations (4) and (5).

$$\Delta P = Av2 + Bv \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

with, A=746.57 & B=48.426 coefficients. These were used to find out inertial resistance C2 and viscous resistance $1/\alpha$ by following equations,

$$A = C2 * \tfrac{1}{2} * \rho * \Delta n \qquad \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

$$B = \mu/\alpha * \Delta n \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Where μ - dynamic viscosity, ρ= air density in kg/m^3 and Δn – Thickness of porous zone (fabric) in mm.

From these equations, we got, C2 = 451441 m-1 and $1/\alpha$ =1002322318 m-2. The seatings of the porous zone under Velocity Resistance Formulation were defined as shown in Fig. 4. With increasing time, the permeability increases in every cell of the porous zone. Therefore, for every time step, new values of inertial and viscous resistance are computed to account for the aerosol deposition in every cell.

4) Solution And Convesrgence

The solution method named pressure velocity coupling was selected in ANSYS. Initialization of solution for all zones was accomplished. Convergence is crucial in computational analysis, as fluid movement involves complex models like turbulence and mass transfer. Under the convergence criterion, iterative solutions are run. The process should continue until the solution field stops changing. In the proposed work, the solution was calculated in successive time steps until the convergence criterion was met. The convergence criterion was the point where the residual variable values reach below 1e-14 as shown in the residual plot of Fig 5. where the solution gets converged. The calculations were run and the fluid flow statistics were observed in ANSYS.

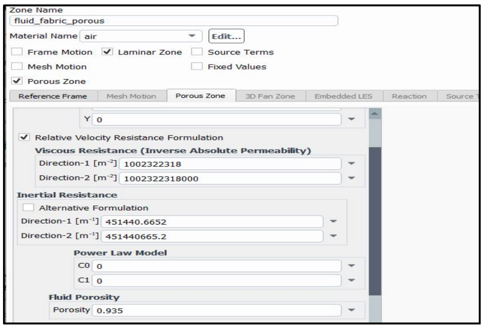


Fig 4. Porous zone settings

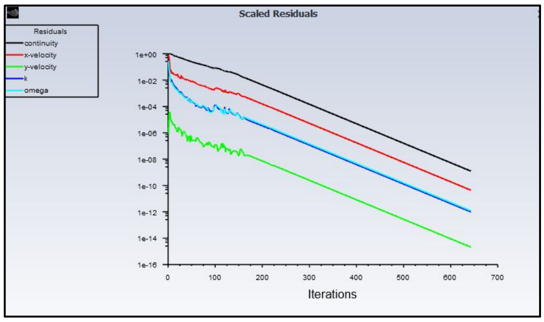


Fig 5. Residual convergence for current simulation: 1e-14

III. RESULTS AND DISCUSSION

All nonwoven filter fabric samples prepared were tested for multiphase flow in ANSYS. The initial pressure was set to 40 CFM. The pressure field across the filter duct is shown in the first Figure 6. It can be observed that a significant pressure drop occurs within the porous region during filtration.

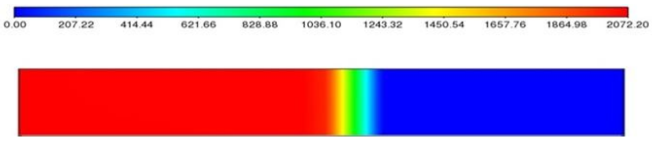


Fig. 6. Pressure contour at inlet and Outlet

It showed that, at the inlet pressure is higher and at the porous interface and was suddenly dropped because of resistance to the flow created by the fabric unit. Figure 7 shows the velocity component distribution of the fluid flow across the filter duct. It represents that the velocity at the inlet is also higher and slows down in the porous zone. A fixed number of particles were passed through the filter duct and particle trajectories were recorded.

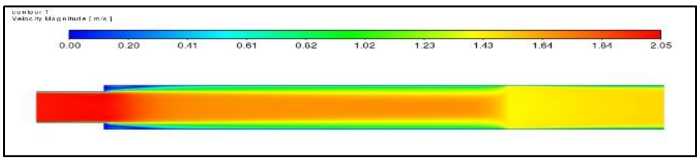


Fig 7. Velocity contour across the duct

Figure 8. shows the behaviour of particles with different diameters say 0.01mm, 0.02 mm, 0.03 mm, 0.04 mm, 0.05 mm & 0.06 mm in the porous or fabric zone. It was observed that the particles having diameters greater than 0.04 mm trapped in the fabric zone and others having diameters 0.01, 0.02, 0.03 & 0.04 mm escaped through the fabric or filter unit.

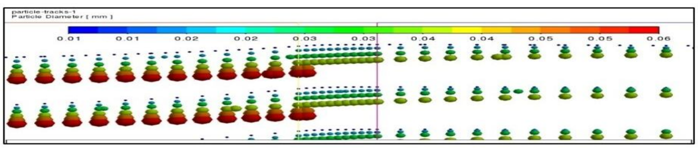


Fig. 8. Particle flow trajectory for sample No.4

In another case as shown in Fig. 9 most of the particles were trapped in the porous fabric zone indicating increased filtration efficiency.

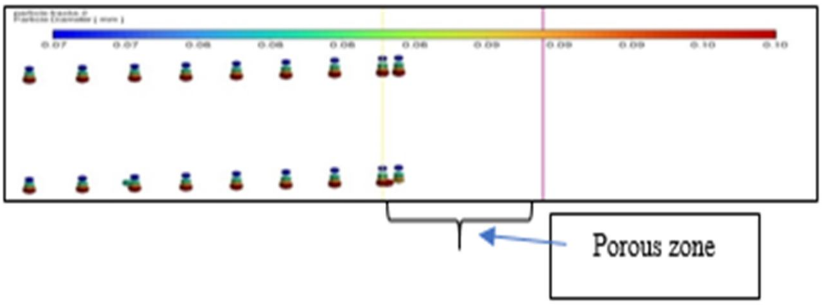


Fig 9. Max particle trapping in the porous zone

The efficiency of filtration was estimated by using the following equation (6) to find the number of particles that vanish from the air after filtering:

$$E=1-N\_out/N\_in \qquad (6)$$

Where Nin, is the total amount of particle at inlet which were traced and Nout denotes the total amount of particle at the outlet which were escaped. Table II shows the total number of particles passed, trapped by the porous zone and escaped from it for a fabric sample having 62.5 % experimental efficiency. The porosity of the sample was 0.943. All the nonwoven samples procured from the nonwoven industry were tested for dust filtration. Table III shows the pressure variations at boundaries of filter duct and across the fabric sample. Significant drop in pressure was observed across the fabric region. The percentage error between the numerical simulation results and the experimental values of filtration efficiency for all samples was within 5%.

TABLE II. RESULTS FOR SAMPLE WITH EXPERIMENTAL EFFICIENCY 62.5%

Sr. No	Parameter	value
1	Total no. of particle traced	210
2	Total no. of particles trapped	126
3	Total no. of particles escaped	84
4	Fabric efficiency by CFD	60 %

TABLE III. RESULTS FOR PRESSURE DROP FOR THE SAME SAMPLE

Wall position	Total Pressure, Pa	ΔP, duct	ΔP, fabric
inlet	2073.5426	2072.18	1968.11
interior_filter_in	2021.3491		
interior_filter_out	53.234952		
outlet	1.3608302		

IV. CONCLUSION

A CFD model was developed by using the Euler-Lagrangian frame to investigate the dust and airflow in the nonwoven fibrous filter. The standard k-ε and K-ω turbulence model combination with the DPM model with standard function embedded in ANSYS-Fluent was used. User-defined functions for particle injection and distribution were developed. The model was built to obtain the required data and validated for getting filtration performance in the computational domain. The following conclusions can be drawn from the study: -

- The air with dust flow field of the nonwoven filter media was implemented in real-time. The viscous resistance and inertial resistance were obtained from the pressure curve, which was provided to the porous media in CFD as the initial parameter. The filtration behaviour was successfully visualized with CFD.
- CFD_DPM modelling was established in ANSYS-fluent for nonwoven porous media to simulate the filtration efficiency and pressure drop in the depth filtration. The function of particle trapping in porous media and the dynamic change of pressure drop during dust loading was realized.
- By controlling the porosity of the porous media, the different trapping mechanism were developed to realize the different distribution forms of particles along the thickness direction. Under the same dust loading, it was observed that with the increase of porosity, more particles will be escaped by the downstream cell reducing efficiency. The pressure drop also changes with the porosity values.
- ANSYS is an effective tool for simulating gas-solid two-phase flow in dust filters and can be to guide the design and optimization of dust filters.

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