

3D SIMULATION OF AEROSOL DEPOSITION AT A COMPOSITE NONWOVEN OF ELECTROSTATICALLY CHARGED WOOL AND POLYPROPYLENE FIBERS

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Abstract

Nonwoven filter media for aerosol filtration are subject to comprehensive analyses for characterization and optimal design referring to specific applications. Particularly for newly introduced filter media, 3D simulation of the aerosol filtration process for different fiber compositions and states of charge can accelerate the development process and improve the adjustment to specific needs.

In previous studies with the analysis and simulation software DNSlab[®], the modeling of 3D fluid flow, electric field, particle transport and deposition in filter media was validated by matching measured pressure drops and filtration efficiencies with simulation results for exemplary synthetic fiber nonwoven. An uncertain and difficult to determine modeling parameter was the distribution and amount of electric charge on the fibers.

In the present study, a new innovative nonwoven material is investigated: the EMP-160 material of Lanaco's EcoStatic[®] product family of filter media is composed of natural wool and synthetic polymeric co-fibers, both having distinct electrical charge properties. The filter efficiencies are examined in several test series. In the first step, the filter media are discharged, and the filter efficiency is determined for uncharged fibers. In the second step, the untreated and charged filter media are examined. Electrostatic Force Microscopy (EFM) measurements are performed to gain insight into the surface charge of the fibers. The results of these measurements provide a charge distribution on the fiber surface, which is reproduced in the 3D simulation.

The pressure drop and fractional filter efficiencies with particle diameters in the range between 0.01 μm and 1 μm are simulated for the charged and uncharged case. The simulation results are compared to the experimental data, showing a good agreement.

Keywords

Wool, Nonwoven, Electrostatic, Aerosol Filtration, Simulation, CFD

Background

Electrostatic charge distribution on fibers is the most unsecure parameter of aerosol deposition processes in nonwoven.

In preceding work with DNSlab, lacking detailed experimental data on the charge distribution and charge amount on the fibers' surface, various possible surface charge distributions were presumed. It was also shown that assuming various distributions and amounts of charge, and then comparing the resulting simulated filtration efficiencies to experimental data until they match, enables a conclusion on the real charge status. [Kerner2020]

Especially for Lanaco's new composite material class EcoStatic of natural wool and synthetic fibers, which is newly introduced into the market, there is a need for adjustment of the material parameters to specific requirements of various applications. The EcoStatic EMP-160 nonwoven was analyzed experimentally particularly accurately with respect to the charge distribution.

Objectives

The first objective is to reconcile the novel experimental findings on the charge distribution on the EMP-160 nonwoven with the DNSlab simulation approach shown in Kerner's work [Kerner2020].

Secondly, the simulation approach should be validated respectively calibrated for Lanaco's EcoStatic nonwoven product family to show the operational readiness of DNSlab for industrial rapid prototyping of nonwoven filter media.

Experimental Setup

The EMP-160 material has the following material properties.

- Mass per Unit Area: 160 g/m²
- Thickness: 3.8 mm according to ISO 9073-2
- Solid Density: Wool 1.34 g/cm³, PP 0.91 g/cm³
- Fiber Diameter Distribution determined by Optical Fiber Diameter Analysis:
Wool: 20 – 30 µm, PP 10 – 17 µm
- Mass Shares: Wool 70%, PP 30%

Fig. 1 shows SEM images of the material. You can see that the fibers are uniformly distributed, that they are only slightly curved and that they have an almost spherical cross section.

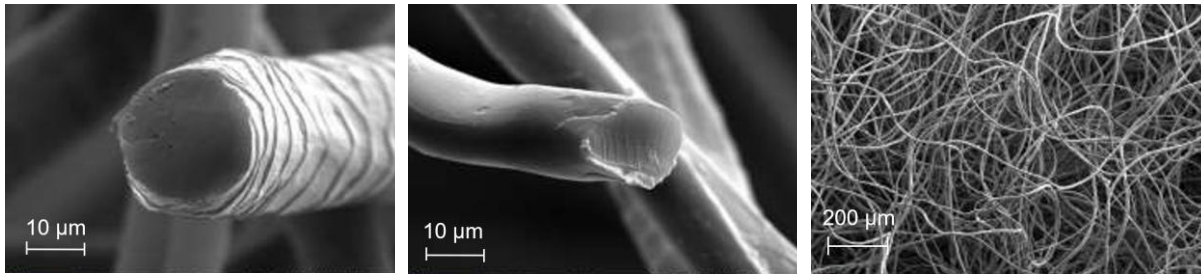


Fig. 1: EcoStatic EMP-160 filter medium: SEM images of a wool fiber (left), a co-fiber (center) and the composed material (right).

The charge distribution on single fibers of wool and PP was measured with the EFM technique, see Fig. 2.

Pressure drop and filtration efficiencies were measured at a DEHS aerosol test rig at 0.14 m/s flow velocity.

To characterize the material in the discharged state, it was discharged by IPA vapor.

Modeling Method

The 3D fiber structure model is generated corresponding to the experimental characterization of the EMP-160 material. In particular, the charge distribution on the fibers is modeled according to the EFM results.

Then, as described by [Kerner2020]

- the air flow field, meaning the local pressures and velocities, are computed by solving the steady-state Stokes equations for conservation of mass and momentum
- the electric field is computed by direct numerical integration of the respective surface integrals with dimensionless surface charges; because of the linear nature of the corresponding integral equation, the resulting dimensionless electric field must just be multiplied with constant factors to obtain it in physical unit C/m² for arbitrary field strengths
- the trajectories of 1 million particles with a Boltzmann charge distribution are computed, taking into account Coulomb and Image forces, Electrophoresis and Diffusion; a particle which contacts a fiber is evaluated as deposited.

The computations of the flow field, electric field and particle trajectories are conducted on a Windows gaming PC with i7-14700K processor and 96 GB DDR5 RAM, using 28 parallel CPU threads.

Additionally, an estimation of the amount of charge on the fiber surface corresponding to [Liu2018] was compared to our findings.

Results

Fig. 2 shows the EFM result and the corresponding models of wool and PP fibers. The different phases of the model fibers were assigned negative and positive dimensionless charges, representing a bipolar surface charge of the fibers.

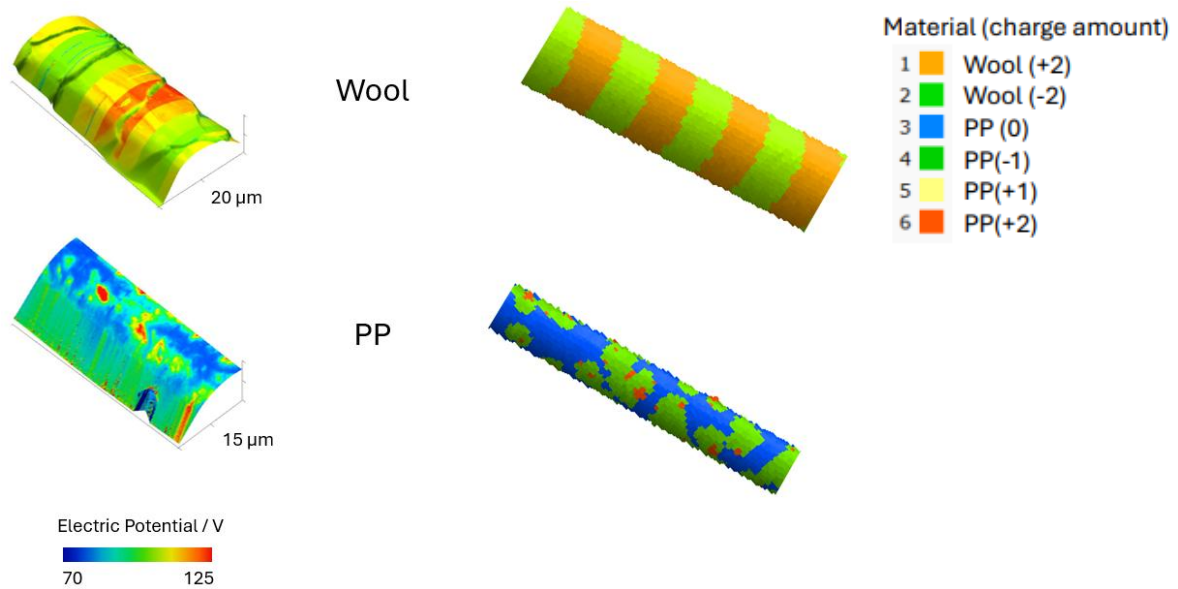


Fig. 2: EFM result (left), model fibers (center), assignment of dimensionless surface charge to model phases (right).

The model of the EMP-160 nonwoven is generated by a random distribution of the model fibers shown in Fig. 2. The nonwoven model has a size of 600 x 600 x 2700 voxels (hexahedron grid cells) with a voxel edge length of 1.6 μm , see Fig. 3.

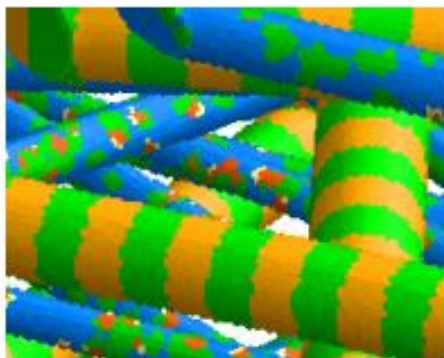
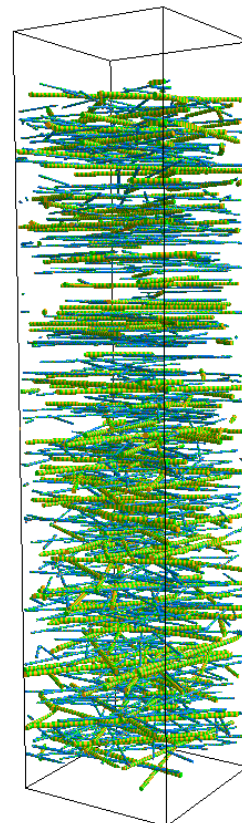


Fig. 3: Detail of the nonwoven model (top) and complete nonwoven model of the EMP-160 material (right).



Tab. 1 shows the duration of the computations, the results are displayed in Fig. 4 and 5.

Tab. 1: Duration of the computations.

	Flow Field	Electric Field	Particle Trajectories
Computation Time	4.5 Hours	40 Hours	15 Minutes

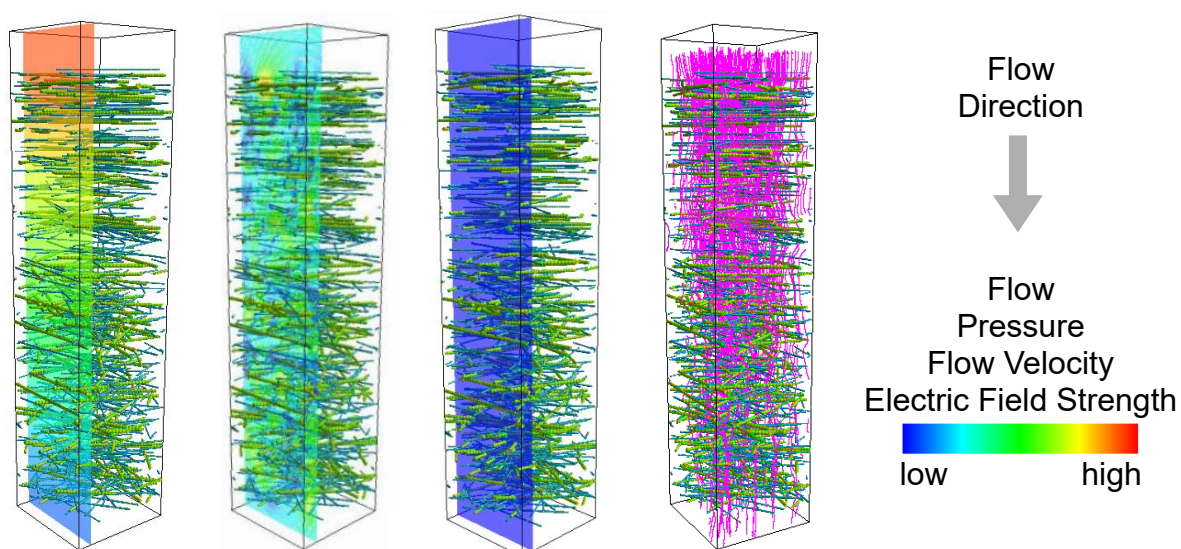


Fig. 4: 2D slices of the 3D flow pressure field (leftmost), flow velocity field (left) and electric field (right); particle trajectories (rightmost).

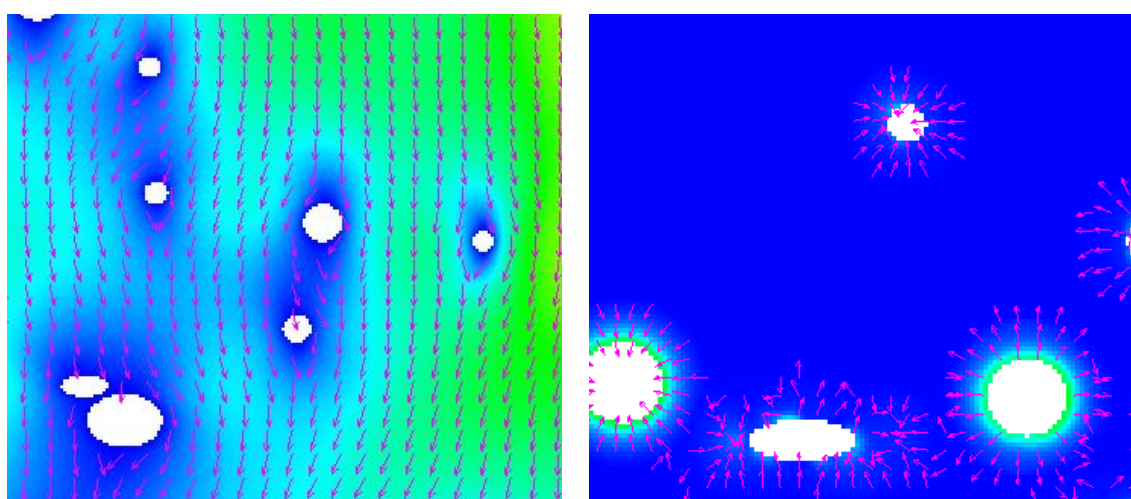


Fig. 5: Details of the flow velocity field (left) and the electric field (right).

The experimental and simulated pressure drop agree as shown in Tab. 2.

Tab. 2: Comparison of measured and simulated pressure drop of the EMP-160 material.

	Experimental	Simulated
Pressure Drop / Pa at 0.14 m/s Air Flow	8.7	7.98

Fig. 6 shows the result of simulated filtration efficiencies with varied surface charge amounts.

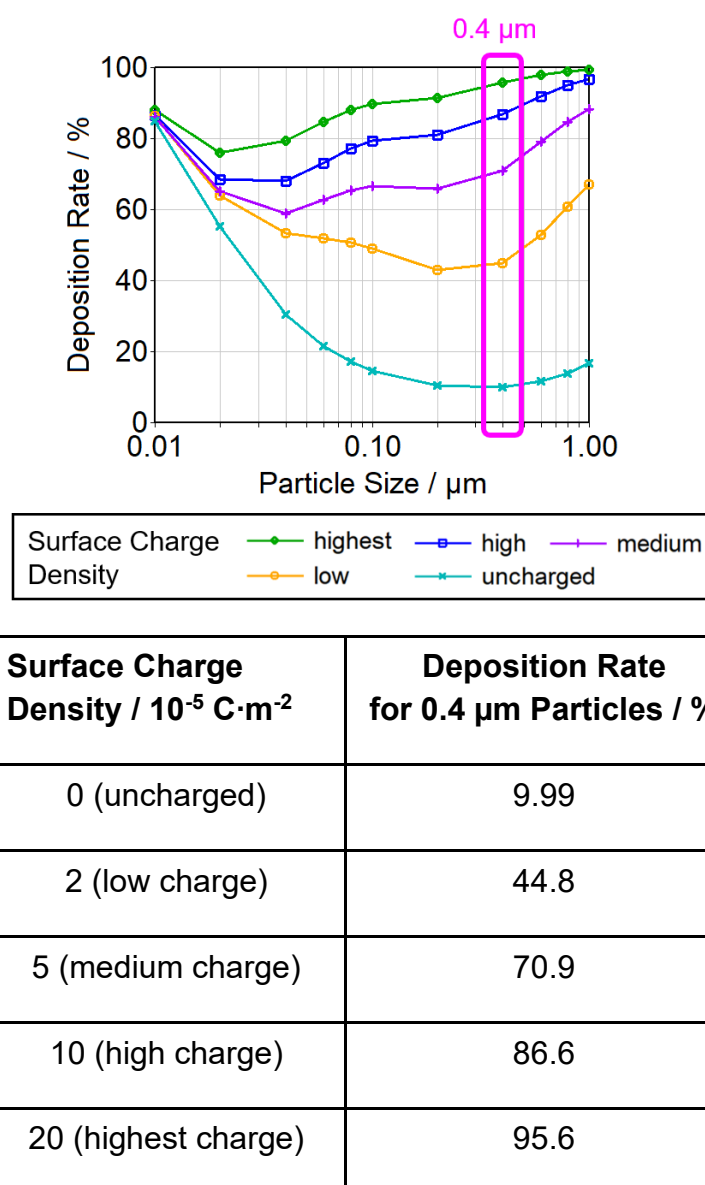


Fig. 6: Simulated fraction deposition rate curves with varied charge densities (top; surface charge density values are multiplied with dimensionless charge amount), corresponding deposition rates for 0.4 μm particles (bottom).

Tab. 3 shows the measured and simulated deposition rates of 0.4 μm particles in comparison. The highest charge shown in Fig. 6 fits best in the charged case.

Tab. 3: Comparison of measured and simulated 0.4 μm particle deposition rates of the EMP-160 material.

Deposition Rate / % for Particle Diameter 0.4 μm	Experimental	Simulated
with uncharged fibers	3.95	9.99
with charged fibers	95.99	95.6 for highest charge

Surface charge density corresponding to [Liu2018] is $1.42 \times 10^{-6} \text{ C/m}^2$ which is significantly too small to match the experimental data.

Conclusion

First, EFM has been shown to be suitable to clarify the *charge distribution* on microfibers. By comparing measured filter efficiencies to DNSlab simulation results for varied amounts of charge, the *amount of charge* can be determined. The estimation of surface charge amount by [Liu2018] was found to be underestimated for Lanaco's EcoStatic EMP-160 material.

Second, the simulation method has been shown to be applicable to adjust the composition of Lanaco's EcoStatic nonwovens for industrial applications by quick and cost effective rapid prototyping with DNSlab to reduce experimental effort.

References

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