Filtration of micro-particles within multi-fiber arrays by adhesive DEM-CFD simulation

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Comparison between parallel and staggered arrays

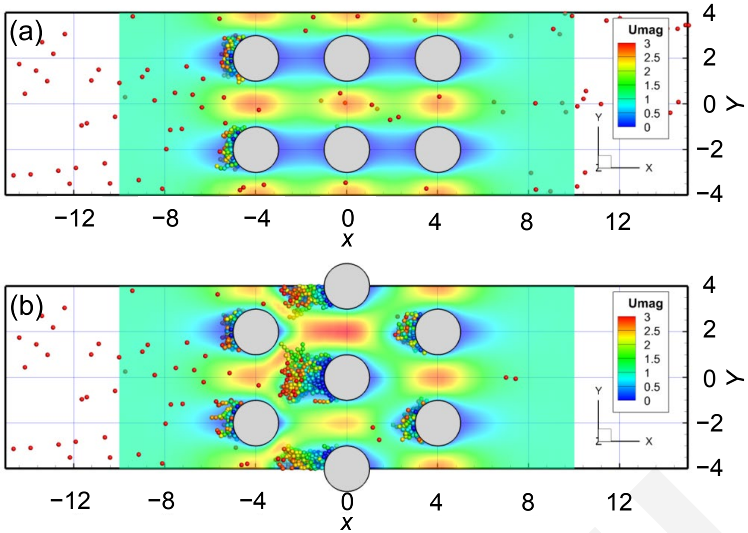


Fig. 1 Schematics of simulated domains with a parallel array (a) and a staggered array (b) viewed from above. Umag is the fluid velocity non-dimensonalized by the superficial filtration velocity

Table 1 Physical parameters used in simulations

Physical parameters	Value	Unit
Particle and fiber		
Particle radius, r_p	1.0	μm
Fiber radius, r_f	10.0	μm
Particle mass density, ρ_p	2500	kg·m^{-3}
Elastic modulus, E	2×10^{7}	Pa
Poisson ratio, σ	0.33	--
Restitution coefficient, e	0.8	--
Work of adhesion, w	20.0	mJ·m^{-2}
Gas		
Gas viscosity, μ	1.79×10^{-5}	Pa·s
Gas density, ρ_g	1.25	kg·m^{-3}
Superficial filtration velocity, U	0.2	m·s^{-1}

- The computer simulation was performed in a three-dimensional rectangular domain, in which fibers are arranged in different types of arrays.
- In this section, with the aim of comparing the filtration performance of parallel and staggered arrays, we positioned the fibers as shown in Fig. 1.
- The superficial filtration velocity was 0.2 m·s^{-1}. The fiber radius was 10 μm, which was determined based on the real size of fibrous material normally used in industry. The particle radius was set at 1 μm, which can well represent micron particulate matter with an aerodynamic diameter smaller than 2.5 μm.

Comparison between parallel and staggered arrays

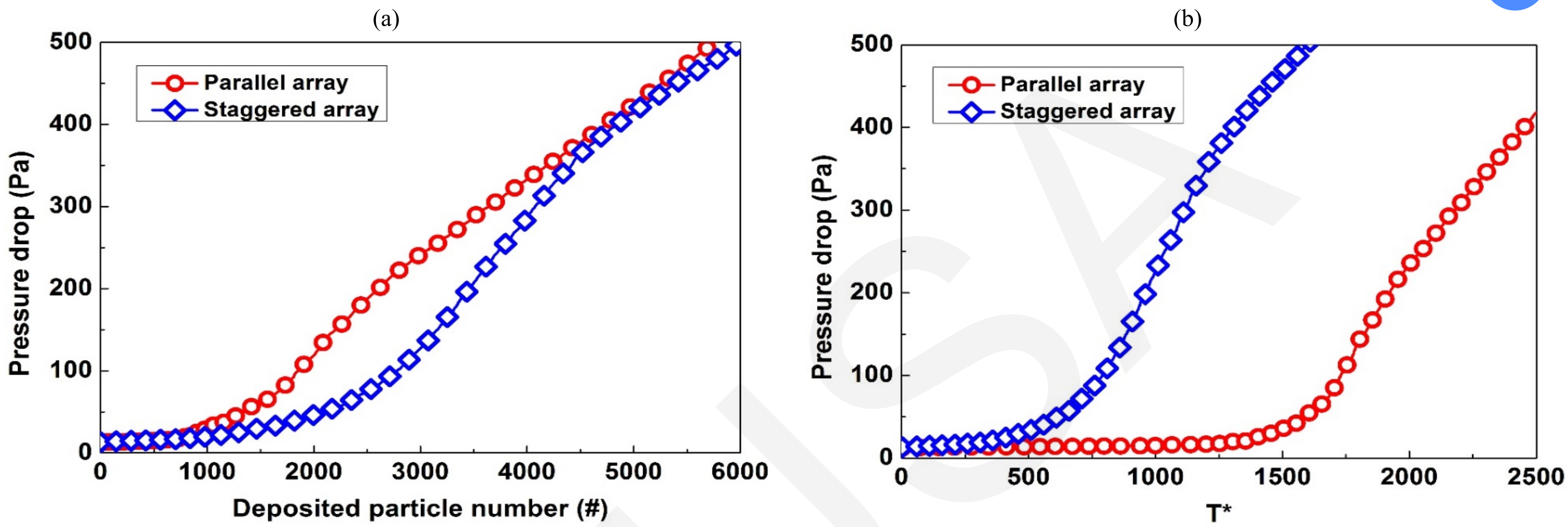


Fig. 2 Pressure drop variation with deposited particle number (a) and dimensionless time (b)

Table 2 Deposited particle number and dimensionless time at the end of two stages

Types	Clean filter stage		Clogging stage	
	N_{dep}	T*	N_{dep}	T*
Parallel	1364	1595	2586	1915
Staggered	2560	737	4483	1216

- For the same number of captured particles, the staggered array always had a lower pressure drop than the parallel array.
- This is because in the staggered array, particles tended to deposit on the first two layers of fibers (there were actually five fibers), while in the parallel array, particles were deposited mainly on the first layer alone (there were only two fibers).

Comparison between parallel and staggered arrays

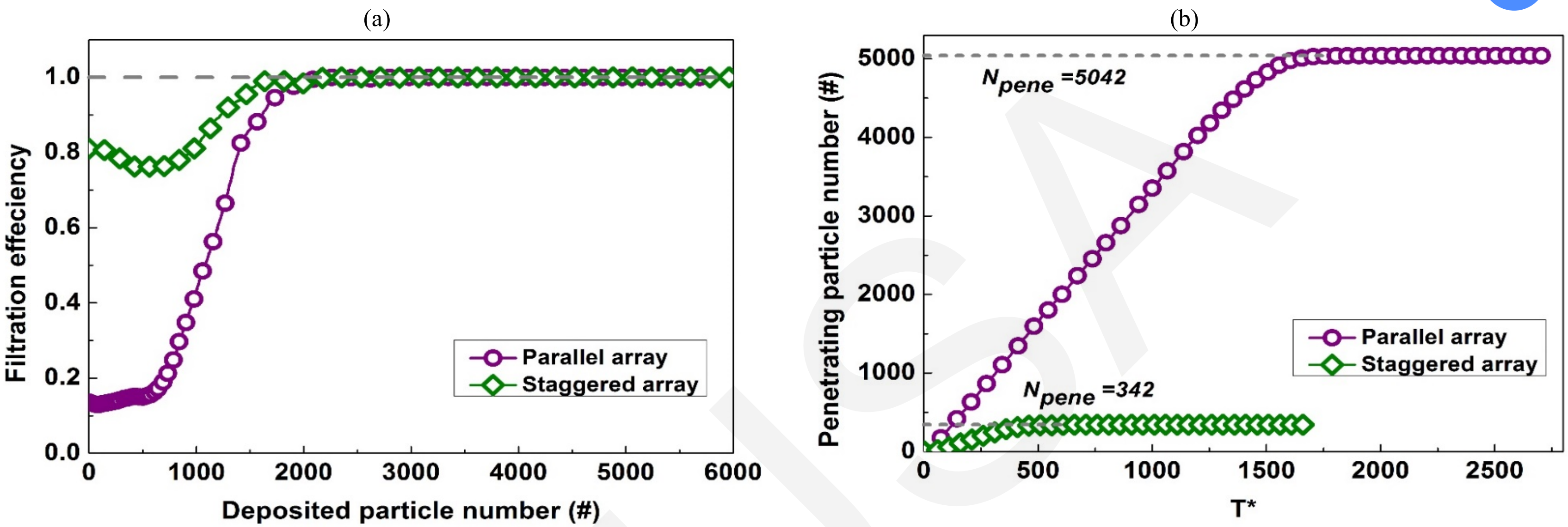
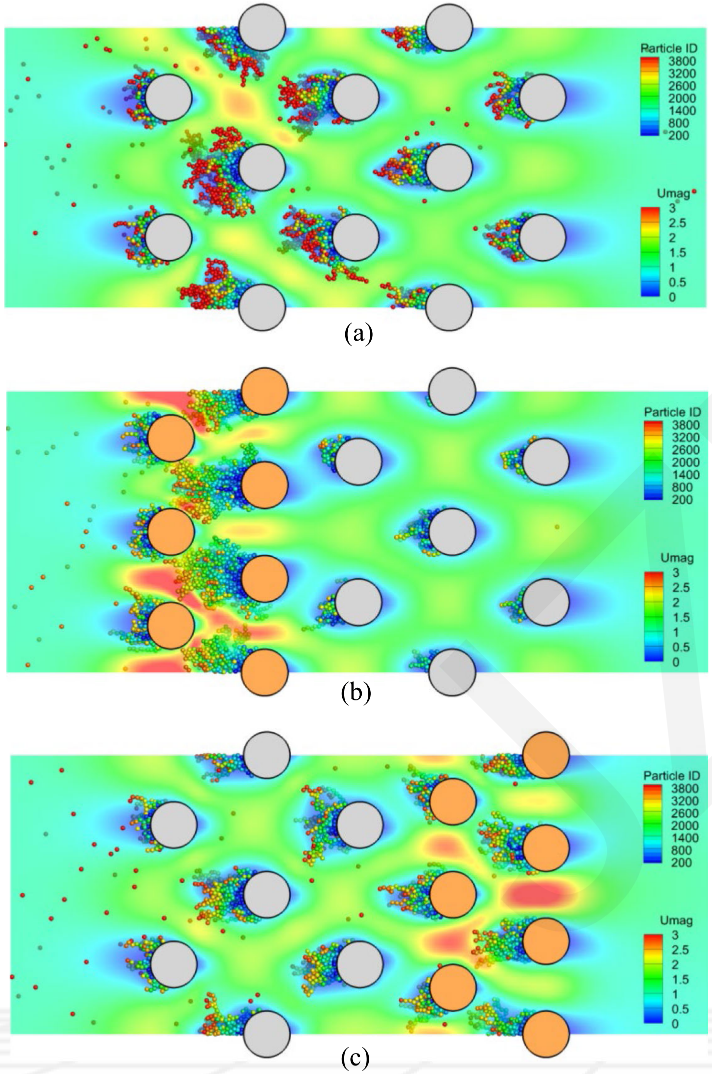


Fig. 3 Filtration efficiency as a function of deposited particle number (a) and penetrating particle number N_{pene} as a function of dimensionless time (b)

- Even in the initial clean filter stage in which particles easily penetrate, the filtration efficiency of the staggered array (around 0.76) was significantly higher than that of the parallel array (around 0.14).
- However, for the staggered array of fibers, particles that penetrate through the front layer will run into the subsequent layer and still have an opportunity to be captured. This dramatically increases the filtration efficiency in the initial clean filter stage and even the clogging stage.
- Note that the filtration efficiency decreased only slightly from about 0.81 to 0.76 in the clean filter stage. This is due mainly to the hydrodynamic effect of the deposited particles on the fluid field, which results in more particles flowing with the fluid and crossing the staggered fibers.
- Particles kept penetrating until the filtration efficiency reached unity, signaling a transition from the clogging stage to the cake filtration stage.

Comparison between different densification modes of the staggered array

Fig. 5 Schematics of the regular staggered array (a), the staggered array densified in the two front layers (b), and the staggered array densified in the two back layers (c)



- We further compared the filtration performance of the staggered array with two different modes of densification, which we believed would be helpful for the advanced design of practical filters.
- Fig. 5a shows a regularly staggered array. It includes five layers of fibers positioned with a layer distance of 4*L*. In each layer, the fiber separation, *W*, was kept as 6*L*.
- We then arbitrarily densified the arrangement of fibers in a layer by changing the fiber separation from 6*L* to 4*L*, and we set up the cases of two densification modes. In one case the densification was in the two front layers (Fig. 5b), and in the other case it was in the two back layers (Fig. 5c).

Comparison between different densification modes of the staggered array

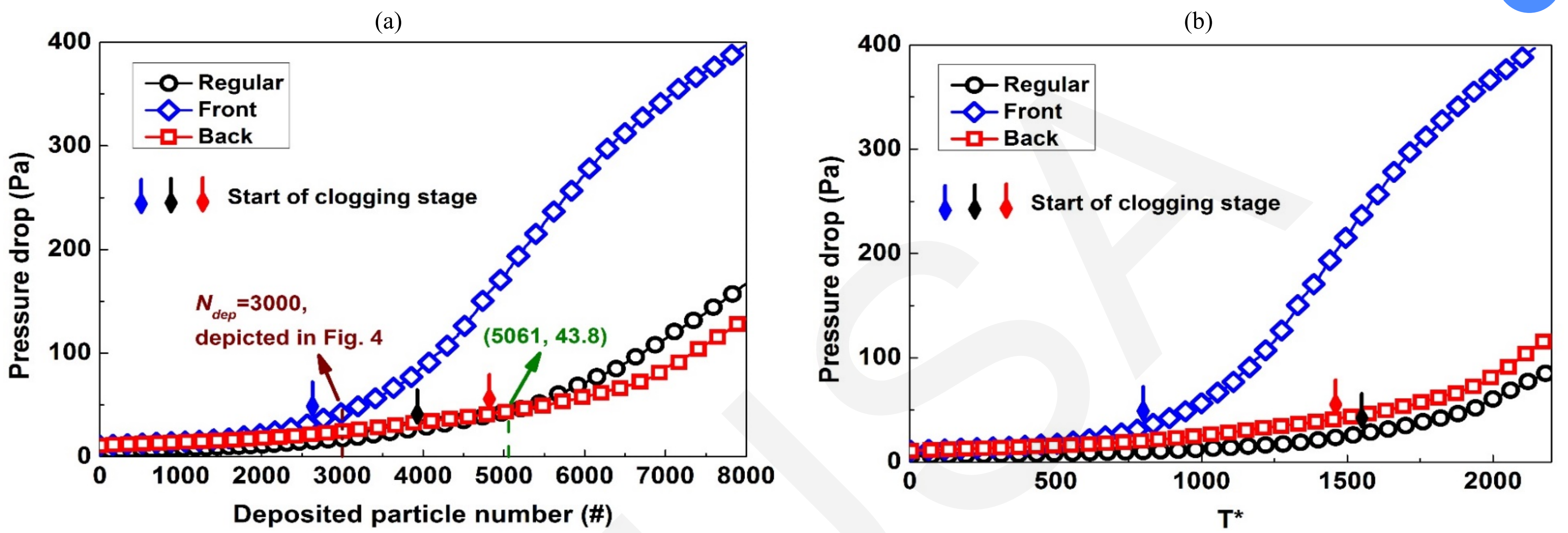


Fig. 6 Pressure drop variation with deposited particle number (a) and dimensionless time (b). "Regular" represents the case with regular staggered array, and "front" and "back" represent cases with densification in front layers and back layers, respectively

- The staggered array with densification in the two front layers had a notably higher pressure drop when the number of particles captured was the same (Fig. 6a).
- As shown in Fig. 5b, more particles were deposited on the two front layers of fibers, in contrast to both the regular and back densified cases.
- When the deposited particle number reached 5061, the pressure drop in the regular case exceeded that in the back densified case (Fig. 6a). This is because the regular case can enter the clogging stage with much fewer deposited particles, causing the faster increase in the pressure drop.
- It is apparent that the front densified case took the shortest time to enter the clogging stage and then the cake filtration stage (Fig. 6b). In both the regular staggered case and the back densified case, it took longer to enter the clogging stage. The back densified case entered the clogging stage a little earlier than the regular staggered case.

Comparison between different densification modes of the staggered array

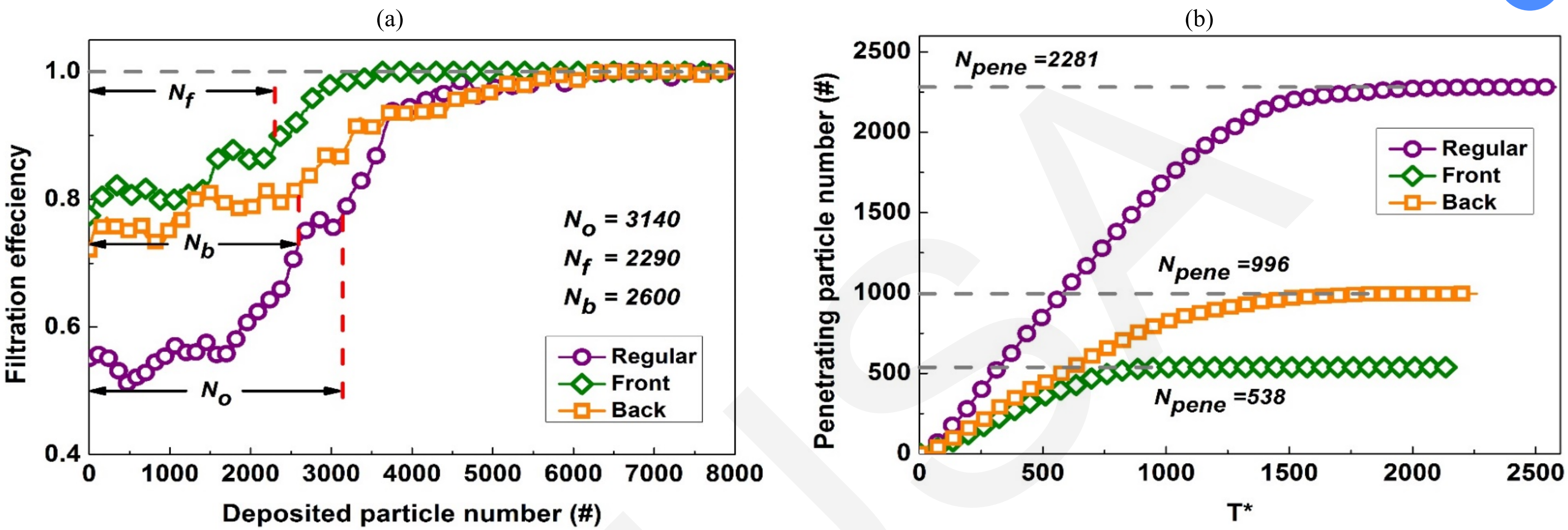


Fig. 7 Filtration efficiency as a function of deposited particle number (a) and penetrating particle number as a function of dimensionless time (b). N_o, N_f, and N_b are the numbers of particles for the oscillating period relating to the regular, front densified, and back densified arrays, respectively

- We analyzed the oscillating period and obtained the number of particles at which the curve stopped oscillating and started moving up continuously. These numbers are denoted as N_o, N_f, and N_b in Fig. 7a. The values indicate that the regular staggered array needed the most particles to go through the oscillating time, and that the front densified array needed the fewest.
- After the oscillating period, the filtration efficiency for the front densified case increased to unity with the fewest particles captured. The filtration efficiency for the other two cases reached unity at a similar number of particles.
- According to Fig. 7b, with only 538 particles penetrating through at the end, the front densified array clearly showed the best performance. For the regular array and the back densified array, although their filtration efficiency reached unity at a similar number of deposited particles, the penetrating particle numbers were quite different.

Comparison between different densification modes of the staggered array

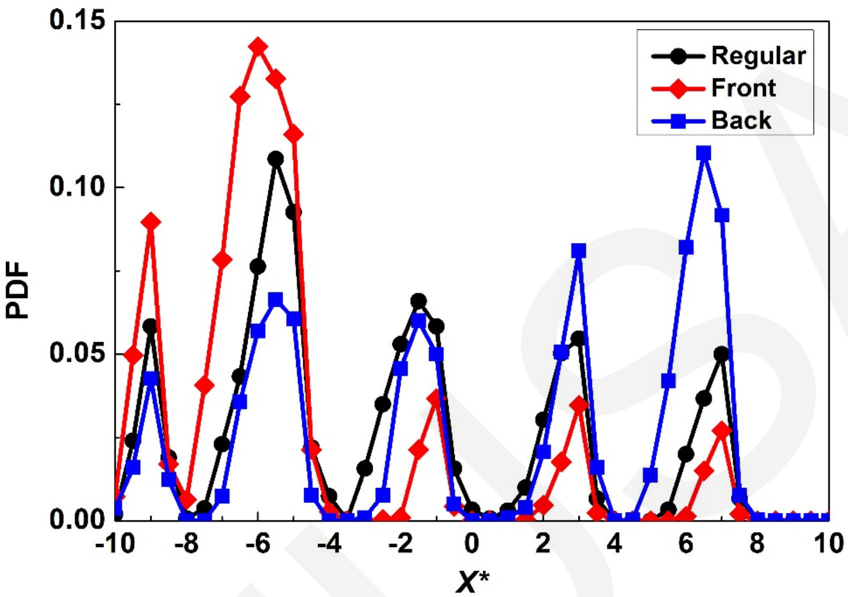


Fig. 8 Probability distribution function of particles deposited along the X-direction (when the deposited particle number equaled 3000)

- First, for the regular staggered array, the second layer captured most particles and had the highest peak. The other four layers captured a similar number of particles. This suggests that the second layer rather than the first plays the most crucial role in capturing particles.
- Compared to the regular case, the front densified array reinforced the effect of the first two layers and thus had fewer particles captured by the three layers at the back. This is much more convenient for the frequent cleaning of dust from filters (e.g. a baghouse filter) and their long-term use, because most particles stay in the front layers and do not penetrate deeply.
- For the back densified case, more particles were captured by the two layers at the back. The particles penetrating the first several layers had a good chance of being captured by the last two layers. Considering the much lower pressure drop in comparison with the front densified case, this suggests that the back densified array should be used for disposable filtration devices, e.g. personal breathing masks.

Conclusions

- The staggered array entered the clogging stage in a much shorter time, about 46% of that for the parallel array, and had a relatively low pressure drop at the same number of captured particles.

- The filtration efficiency of the staggered array in the initial clean filter stage was significantly higher than that of the parallel array. The penetrating particle number of the staggered array was about one-fifteenth of that of the parallel array, suggesting a better overall filtration.

- The front densified array entered the clogging stage within a significantly shorter time (about 52% of that for the regular array and 55% of that for the back densified array). The back densified array and the regular array showed a similar pressure drop during the filtration process.

- However, the back densified array had a better filtration efficiency than the regular array, although the front densified array performed best with the fewest particles passing through.

- For the front densified array, about 83% of all deposited particles were located in the first two layers, compared with only 48% for the regular array. For the back densified array, about 52% of all deposited particles were captured by the last two layers, compared with only 10% for the regular array.

- These results will help enhance understanding of the underlying physics of fiber filtration with different geometrical arrangements.

Thank you!