Efficiently remove submicron particles by a novel foldable electrostatically assisted air coarse filter

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ABSTRACT

Electrostatic assisted air (EAA) coarse filters combine the benefits of electrostatic precipitators and fibrous filters, achieving high filtration efficiency for submicron particulate matters (PM), low pressure drop, and large dust-holding capacity. For application in heating, ventilation, and air conditioning (HVAC) systems, PM removal technology is required to work at high air duct velocity, for example, 1 to 3 m/s. However, both theory and experience have revealed that the pressure drop will increase at large airflow rates. Here, we developed a novel foldable EAA coarse filter by shaping the polarizing electrodes into a zigzag structure and folding the coarse filter between the electrodes. High filtration efficiency for submicron PM (85.0–94.0\% for 0.3–0.5 \(\mu\)m PM, 92.0–96.5\% for 0.5–1 \(\mu\)m PM) and low pressure drop (5.9–26.4 Pa) at high air duct velocity (1–3 m/s) are achieved by optimizing folding angle \(\theta\) to 45\°. We found that \(\theta\) determines the shape of the PET fold and the nature of electric field, leading to different filtration performances. In order to get the module with better applicability, the optimum \(\theta\) was determined simultaneously by both filtering velocity and effective polarizing area. The results are expected to facilitate the wide application of EAA coarse filters in HVAC systems for a healthy and energy-saving indoor environment.

1. Introduction

Ambient particulate matter (PM) concentrations in developing countries, including China and India, far exceed WHO standards, which may be attributed to the increasing expansion of urban areas [1]. It has become a consensus that PM is harmful to human health [2–4]. Exposure to airborne PM has been associated with increased mortality due to respiratory and cardiovascular diseases [5–7]. Particularly, indoor PM is of great concern because people are exposed to indoor air for more than 80\% of their lifetimes [8]. Indoor inhalable PM is partially from outdoor PM entering the room through natural or mechanical ventilation [9], and partially from indoor PM generated from living activities and chemical reactions [10]. Therefore, effective PM removal technologies for heating, ventilating and air conditioning (HVAC) systems in buildings are required to maintain indoor air cleanliness and protect the health of residents.

High efficiency particulate air (HEPA) filters are one of the most commonly used technologies for PM removal in HVAC systems, usually made of polymer or glass fibers, with a single-pass filtration efficiency of no less than 99.97\% [11,12]. Despite such high filtration efficiency, the pressure drop (air resistance) of HEPA filters is large and rapidly increases as PM deposits its surfaces. The large pressure drop of filters causes not only its own lifetime problem, but also huge power consumption of ventilators, both of which result in the high cost of filtration [13]. For example, a MERV13 (Minimum Efficiency Reporting Values 13) filter has an initial pressure drop of 11.3 Pa, which will rapidly increase to 250 Pa after depositing 9.5 g/m\textsuperscript{2} PM on its surface [14]. To overcome the large pressure drop problem of conventional HEPA filters, researchers have fabricated electrospun nanofibers to simultaneously achieve lower pressure drop and higher PM filtration efficiency [15–20]. For example, Bortolassi et al. fabricated silver/polyacrylonitrile (Ag/PAN) electrospun nanofibers on a nonwoven substrate with a filtration efficiency of 98.65\% for 0.09–0.3 \(\mu\)m particles and a pressure drop of 68 Pa at 0.03 m/s air velocity [21]. However, due to the relatively low dust
loading capacity of nanofiber filters, the service life of electrospun nanofiber filters is shorter than that of conventional HEPA filters [22]. In addition, as a common purification technology, electrostatic precipitators (ESP) are widely used in industry [23]. The pressure drop of ESP is two to three orders of magnitude lower than that of HEPA filters [24,25]. However, the single-pass filtration efficiency of conventional ESP is relatively low, especially for fine and ultrafine particles [26,27].

To avoid their individual shortcomings, combining fibrous filters and ESP is proposed to build new filtration technologies. Some researchers used corona discharge or ion generators to charge particles and subsequently make the charged particles be captured by filters [28–31]. Feng et al. [32] used the electric field of corona discharge to simultaneously charge airborne particles and a filter in the electric field. When the discharge voltage was 25 kV, the filtration efficiency for 0.4 µm particles and a filter in the electric field. When the discharge voltage was 25 kV, the filtration efficiency for 0.4 µm particles was improved from 29% to 97%, with a resistance of 38 Pa at 0.1 m/s air velocity. Instead, Lee et al. [33] charged and polarized particles and filters by two independent electric fields. Under 4.7 kV/cm discharge and 1.4 kV/cm polarization, the filtration efficiency for 0.1–5 µm particles was 99% and the pressure drop was 157 Pa at 2.5 m/s air velocity.

Tian et al. [34] developed a novel compact electrostatic assisted air (cEAA) coarse filter that efficiently removed ambient PM by synergistic particle charging and filter polarization. Further improvement of EAA technology increased the single-pass efficiency for 0.3–0.5 µm PM of a coarse filter from 0.4% to 99.0% [35]. Tian et al. [36] and Gao et al. [37] developed new dielectric hetero-caking (HC) filters by heterogeneously loading high relative dielectric constant (εr) materials on conventional polymer fibers. The high efficiency, low pressure drop, and filter longevity suggest the advantages of multi-functional filter design. EAA HC filters can remove not only airborne PM, but also ozone [36,37], formaldehyde [36], and SVOCs [38]. Electrostatic fields have been reported to inactivate bacteria [39–41]. Thus, with specific electrostatic field strength and the prolonged exposure time, EAA filters will also offer the potential to inactivate bacteria. By combining EAA filtration technology with PM sensors, it will play an important role in industrial pollutant control, clean room operation and healthy environment creation [42].

For application in HVAC systems, PM removal technology is required to work at high air duct velocity, for example, 1 to 3 m/s. Here, we solved the problem of low filtration efficiency and large pressure drop at high air velocities by developing a novel foldable EAA coarse filter module. Having the advantages of fan-energy-saving and large dust holding capacity [43], the foldable EAA coarse filter module is suitable for PM removal in the HVAC system. The polarizing electrodes of the new module were shaped into a zigzag structure, and the coarse filter was folded and installed between the electrodes. We investigated the effects of charging voltage, polarizing voltage, and air duct velocity to 0.3–10 µm PM filtration efficiency, pressure drop, and net ozone production. We adjusted the folding angle (θ) from 180° (no folding) to 60°, 45° and 30°. We found that θ determines the shape of the PET fold and the nature of electric field, leading to different filtration performances. We interpreted the result by calculating the air filtering velocity and electric field simulation. By optimizing θ to 45°, the foldable EAA coarse filter module achieved the highest comprehensive quality factor (CQF), which indicated the best performance considering high efficiency and low energy cost.

2. Methodology

2.1. Polarization modules with different folding angles

As shown in Fig. 1, the new polarization module consists of high-voltage electrodes, grounded electrodes, and a foldable coarse filter. The dimensions of the polarization module are 288 × 200 × 420 mm³ (width × height × length). The high-voltage and grounded electrodes are made of copper and aluminum, respectively. The dimensions of each electrode are 150 × 198 × 1.5 mm³ (width × height × thickness). The high-voltage electrodes (porosity: 0.31) are patterned with 30 mm opening holes and the grounded electrodes with 3 mm opening holes. Each high-voltage electrode is mounted at an angle towards the airflow in the air duct, and each grounded electrode (porosity: 0.20) is mounted in parallel with the high-voltage electrode one-to-one. A 5 kV/cm polarizing field is built by applying ± 15 kV DC (direct current) to the high-voltage electrode and adjusting the distance between the two parallel electrodes to 30 mm. The foldable coarse filter is installed between the two parallel electrodes, attaching to the grounded electrode. The filter is 10 mm thick and made of polyethylene terephthalate (PET).

Supplementary Fig. S1 shows the morphology of the filter with an average fiber diameter of 28.3 ± 8.6 µm. In this study, we developed 4 polarization modules with folding angles of 30°, 45°, 60°, and 180° (without folding). The filter areas for the 4 folding angles are 1272 cm² (30°), 899 cm² (45°), 734 cm² (60°) and 636 cm² (180°), respectively.

2.2. Electric field simulation

Numerical simulation of the electric field was conducted by Ansoft Maxwell EM software (version 12.0, USA) to investigate the influence of folding angles. The polarization field condition for numerical simulation was the same as the experiment, including the applied voltage, the distance between the high-voltage and grounded electrodes. The dimensionless electric field intensity, S(x), is defined by Equation (1).

\[ S(x) = \frac{|E(x)|}{E_p} \]  

where x is the position coordinate; E(x) is the electric field intensity vector at x; E_p is the applied polarization field intensity, equal to 5 kV/cm. The electric field distribution between electrodes can be obtained by simulation, and the influence of various folding angles on the electric field distribution can be quantified.

![Fig. 1. Polarization module schematic: (a) in vertical view; (b) in 3D view.](image-url)
2.3. Filtration test

The experimental setup was on the roof of a two-floor office building in the Tsinghua University campus in Beijing, a site not proximal to heavy traffic, cooking, or industrial sources of pollution. Fig. 2 shows the experimental setup for filtration tests, which consists of a ventilation duct, a coarse filter, an air ventilator, a perforated diffusion plate, a pin-to-plate discharger, a foldable EAA coarse filter module, and measurement instruments. The ventilation duct is made of acrylic, with inner dimensions of 288 × 200 × 1000 mm³ (width × height × length). The air ventilator is installed at the inlet of the ventilation duct to drive outdoor ambient air through the duct at controlled air velocities. A coarse filter and a perforated diffusion plate are installed at the inlet in sequence to remove tiny things from outdoor air and evenly distribute the airflow. We used ambient aerosols as feeding pollutants and used as-received filter to evaluate near-real performance of the filter module for HVAC applications. We found the tested filtration efficiency using above-mentioned method was close to that using uncharged sodium chloride (NaCl) aerosols and uncharged isopropyl alcohol (IPA) treated filter, as shown in Supplementary Fig. S2 and Fig. S3.

The discharge module consists of grounded hollow-plate electrodes and charging pin arrays connected to a 0 ~ ±30 kV adjustable high voltage direct current (HVDC) power supply (P30, GENVOID, 0 to ±30 kV, China). When supplied with adequately high voltage, the pinpoints generate a strong electric field around them to produce a corona discharge [44]. Large quantities of ions are produced and attached to particles passing by the charging pins [45]. The folding polarization module is installed 30 mm downstream of the discharge module and connected to another HVDC power supply (P30, GENVOID, 0 to ±30 kV, China). The voltage and current of the discharge and polarization modules are measured by the power supplies.

As Fig. 2 shows, the number concentrations of 0.3–10 μm particles are measured by an optical particle counter (Aerotrak 9306, TSI Inc., Shoreview, USA) at the upstream and downstream of the filter modules. The ozone volume concentrations are measured by a photometric ozone monitor (Model 205, 2B Tech., Boulder, USA). The pressure drop of the filter module is measured by a differential pressure transmitter (DP-CALC 5825, TSI Inc., USA). The air duct velocity is measured by an anemometer (435–1, Testo, Germany). The air temperature and relative humidity are recorded by sensors (WSZJ-IA, TIANJIANHUAYI, China) and conducted at a temperature of 1 ± 2 ℃ and relative humidity of 30 ± 10%. Outdoor ambient particles are used as a loading source, of which the particle size distribution is shown in Supplementary Fig. S4.

2.4. Performance evaluating parameters

The single-pass filtration efficiency of PM with a specific size, η(dPM), is calculated by Equation (2).

\[ \eta(d_{PM}) = 1 - \frac{C_o(d_{PM})}{C_i(d_{PM})} \]  

(2)

where \( d_{PM} \) (µm) is PM diameter; \( C_o(d_{PM}) \) and \( C_i(d_{PM}) \) are number concentrations (pcs/L) of the downstream and the upstream of the filter module, respectively.

Net ozone production, \( \Delta C_{ozone} \) (ppb), is calculated by Equation (3).

\[ \Delta C_{ozone} = C_{ozone} - C_{ozone}' \]  

(3)

where \( \Delta C_{ozone} \) is the net ozone production (ppb); \( C_{ozone} \) and \( C_{ozone}' \) are the ozone concentration (ppb) at the downstream and upstream of the filter module, respectively.

Besides pressure drop, \( \Delta p \) (Pa), we use an air resistance coefficient, \( \beta \) (Pa·s/m) [46], to evaluate the air resistance of the filter module, which is calculated by Equation (4).

\[ \beta = \frac{\Delta p}{u} \]  

(4)

where \( u \) (m/s) is the filtering velocity perpendicular to the filter surface, as shown in Fig. 3. In a folded filter, \( u \) is calculated by Equation (5).

\[ u = v_{air} \cdot \sin(\theta) \]  

(5)

where \( v_{air} \) (m/s) is the air duct velocity and \( \theta \) is the folding angle. In an unfold filter, where \( \theta = 180° \), \( u \) is equal to \( v_{air} \).

To evaluate both filtration efficiency and pressure drop of filters with a single parameter, quality factor (QF) as a benefit-cost ratio is proposed and calculated by Equation (6) [47].

\[ QF(d_{PM}) = \frac{-ln(1 - \eta(d_{PM}))}{\Delta p} \]  

(6)

For electrostatic filtration with power supplies, not only pressure drop but also the device’s power consumption must be considered in the benefit-cost ratio to avoid overestimation. Thus, Tian et al. proposed a comprehensive quality factor (CQF), in which filtration efficiency, pressure drop and power consumption are all considered [48]. The CQF assumes that the extra power consumption of the improved efficiency is equivalent to the equivalent resistance of the filter. In this way, at the same air velocity and for the same particle size, the CQF and QF can be conveniently compared to distinguish more energy-efficient...
technologies. The CQF for PM with a specific size, CQF \((d_{pM})\), \(\text{Pa}^{-1}\), is calculated by Equation (7).

\[
\text{CQF}(d_{pM}) = \frac{-\ln(1 - \eta(d_{pM}))}{\Delta \rho + \frac{\nu_{air}}{u}}
\]

where \(\eta_{vent}\) is the ventilator efficiency, equal to 0.71; Power consumption, \(P_t\) (W/m²), is calculated by Equation (8).

\[
P_t = \frac{U_d I_d + U_p I_p}{A}
\]

where the subscripts \(d\) and \(p\) stand for discharge and polarization module, respectively; \(U\) (kV) is the supply voltage; \(I\) (mA) is the loop current; \(A\) (m²) is the cross-sectional area of the air duct, equal to 0.576 m². This study compared the QF and CQF of the foldable EAA coarse filter module, and used CQF to decide the optimum folding angle, which made the filter module achieve the best comprehensive performance.

3. Results and discussion

3.1. Influence of folding angle

There is an intrinsic conflict between filtration efficiency and pressure drop (air resistance). In mechanical filtration, the foldable coarse filter will reduce filtering velocity \(u\), therefore maintaining high filtration efficiency and reducing pressure drop \([49]\). As shown in Fig. 3, when folding the filter, \(\theta\) reduces from 180° to 0° and \(u\) reduces from \(v_{air}\) to 0. Since \(d(a)/d(\theta) = 1/2 v_{air}\cos(0.5\theta)\) according to Equation (5), when \(\theta\) is around 180°, \(u\) will not reduce much as \(\theta\) reduces. To obtain a large \(u\) change, we choose smaller \(\theta\) as 30°, 45°, and 60°. For unfold filter, reducing \(u\) will reduce pressure drop and enhance filtration efficiency of an EAA coarse filter module \([50]\). Since reducing \(\theta\) will reduce \(u\), it is expected that reducing \(\theta\) will also reduce pressure drop and enhance the filtration efficiency of a foldable EAA coarse filter module in this study. In this way, a large air duct velocity can be maintained with comprehensively good filtration performance: high efficiency and low pressure drop, i.e., large QF and CQF.

In this section, we investigated how much the pressure drop, filtration efficiency and overall performance (QF and CQF) could be influenced by reducing \(\theta\), and gave and explained the optimal value of \(\theta\).

3.1.1. Influence on pressure drop

As shown in Fig. 4a, reducing air duct velocity \(v_{air}\) would notably reduce pressure drop. When \(v_{air} = 1\) m/s, the pressure drops of filter modules with \(\theta = 30^\circ, 45^\circ, 60^\circ, 180^\circ\) are 5.4 Pa, 5.9 Pa, 8.1 Pa, 16.1 Pa, respectively. While when \(v_{air} = 3\) m/s, they are 26.1 Pa, 26.4 Pa, 35.0 Pa, 81.3 Pa, respectively. However, shrinking \(\theta\) from 45° to 30° (\(u\) is from \(\sim 0.38v_{air}\) to \(0.26v_{air}\)) does not reduce as much in pressure drop as shrinking \(\theta\) from 60° to 45° (\(u\) is from \(\sim 0.50v_{air}\) to \(0.38v_{air}\)). When considering resistance factor \(\beta\), Fig. 4b shows that 45°-folded module has the lowest \(\beta\) among all modules at different air duct velocities, followed by 60°, 180°, and finally 30°-folded module. It indicates that \(\theta = 45^\circ\) is optimal for reducing pressure drop of the foldable EAA filter module.

3.1.2. Influence on filtration efficiency

The total filtration efficiency of an EAA filter module is determined by a combination of mechanical and electrostatic filtration \([37]\). As shown in Fig. 5a, in the total single-pass efficiencies (① with charging and polarizing voltages), taking the 30°-folded module as an example, the mechanical filtration (①) only contributes 5.1%, the particle charging contributes most (86.0%), and the filter polarization contributes additional 3.4%. When the air duct velocity is 1 m/s, the mechanical (without voltages) filtration efficiency for 0.3–0.5 μm particles increases from 2.2% to 5.1% by folding the module with \(\theta\) from 180° to

![Fig. 3. Diagram of the airflow through the folded filter.](image-url)

![Fig. 4. (a) Pressure drops and (b) air resistance coefficient \(\beta\) of foldable EAA coarse filter module with various folding angles (\(\theta = 180^\circ, 60^\circ, 45^\circ\) and \(30^\circ\)) when air duct velocity varies from 1 to 3 m/s.](image-url)
30°. The result is consistent with our understanding of mechanical filtration: reducing θ would reduce $u = v_{\text{air}} \sin(0.5\theta)$ and therefore enhance filtration efficiency. The total filtration efficiencies follow similar trends with mechanical efficiencies, that they increase as θ decreases. By folding the module with θ from 180° to 30°, the single-pass filtration efficiency for 0.3–0.5 μm particles increases from 91.8% to 94.5%. However, the filtration efficiency does not follow the trend at higher air duct velocities (1.5–3 m/s), as shown in Fig. 5b. For example, at 3 m/s air duct velocity, the 45°-folded module achieves the highest filtration efficiency (85.0%) among all modules, followed by 30° (80.7%), 180° (80.3%), and finally 60°-folded module (79%). As expected, the total filtration efficiency and air duct velocity have a substantial negative relationship for all modules due to the shorter PM retention time in the module at higher air duct velocity. With air duct velocity increasing, the total filtration efficiency of the 45°-folded module reduces less than the other modules, achieving the highest filtration efficiency at 1.5–3 m/s air duct velocities. While the total filtration efficiency of the 30°-folded module reduces most among all modules, making it less effective than the 45°-folded module at 1.5–3 m/s air duct velocities. This result is probably related to the filtering velocity (which is discussed in Section 3.1.1 and Section 3.1.2) and the effectiveness of the polarizing electric field (which is discussed in Section 3.1.4).

3.1.3. Influence on comprehensive performance

We use QF and CQF to evaluate the comprehensive performance of the EAA filter module. QF considers the filtration efficiency and pressure drop, and CQF considers the filtration efficiency, pressure drop and power consumption. A preferable module with high filtration efficiency, low pressure drop and low energy consumption should have a large CQF. Fig. 6 shows QFs and CQFs for 0.3–0.5 μm particles of the filter modules at 1–3 m/s air duct velocities. The results in Fig. 6a highlight that the folded filters are of more advantage than unfold ones owing to their increased efficiency and reduced pressure drop. At air duct velocities of 1.5–3 m/s, the 45°-fold module achieves the greatest QFs of 0.25 to 0.07 Pa$^{-1}$ because of its highest filtration efficiency and relatively low pressure drop. Meanwhile, as shown in Fig. 6b, CQFs show similar results and trends with QFs when considering power consumption, because the power consumption of the whole filter module is determined by the discharge module, which would not be influenced by θ. Since the 45°-folded module shows the largest QF and CQF at high air velocity (1.5–3.0 m/s), 45° is the optimal θ for the filter polarization module to be applied in HVAC systems.

3.1.4. Electric field simulation

We found that for foldable EAA filters discussed in Section 3.1.1 and Section 3.1.2, reducing θ does not always allow for a decrease in pressure drop and an enhancement in filtration efficiency. We suppose that the filtration efficiency of foldable EAA filters is affected by both $u$ and the effective area of the polarizing electric field. The effective polarizing area is defined as the ratio of the area with dimensionless electric field intensity $S(x) \geq 0.9$ and the whole area between the electrodes. A larger effective polarizing area reflects a more uniform distribution of the effective polarizing electric field. Fig. 7 shows the dimensionless electric field intensity distribution and the electric field vector diagram of three foldable EAA coarse filter modules. Taking the
unfold \( \theta = 180° \) module as an example, 70.1% of the area between the electrodes reached \( S(x) \geq 0.9 \). Therefore, the effective polarizing area for the unfold module is 0.701. The effective polarizing areas for 60°, 45°, and 30°-folded modules were 0.473, 0.381, 0.195, respectively.

In summary, the effective polarizing area significantly reduces when the folding angle reduces, due to the hollow structure of electrodes and the distance between electrodes and filters. Therefore, the electrostatic filtration efficiency enhanced by polarization is reduced. For the 45°-folded module, the effective polarizing area can be maintained at 0.381, and the filtering velocity is effectively reduced to 1.15 m/s at air duct velocity.

Fig. 7. Simulation results for (a)-(c) the dimensionless electric field intensity (ratio of the overall and applied electric field) (accuracy: 1 mm) and (d)-(f) electric field vector diagram of the foldable EAA coarse filter module. (a)(d) \( \theta = 30° \). (b)(e) \( \theta = 45° \). (c)(f) \( \theta = 60° \).

Fig. 8. (a) Ozone production and single-pass filtration efficiencies for 0.3–0.5 \( \mu \)m particles and (b) 0.3–10 \( \mu \)m particles of the 45°-folded module at 1 m/s air duct velocity; The charging voltage varies from 0 to 9 kV and the polarizing voltage is 0 kV. (c) Single-pass filtration efficiencies for 0.3–0.5 \( \mu \)m particles and (d) 0.3–10 \( \mu \)m particles of the 45°-folded module at 1 m/s air duct velocity; The charging voltage is 8 kV and the polarizing voltage varies from 5 to 20 kV. The error bars in the (a)-(d) are the standard deviations for 4 experimental observations.
velocity of 3 m/s, which makes the 45°-folded module achieve the optimal performance.

3.2. Influence of charging and polarizing voltages

As discussed above, the 45°-folded module not only has a low pressure drop, but also has high filtration efficiencies at high air duct velocities (1.5–3 m/s). Therefore, we chose to investigate the detailed performance of the 45°-folded module under different charging and polarizing conditions.

Fig. 8a shows the ozone production and single-pass filtration efficiencies for 0.3–0.5 μm particles of the 45°-folded module with varying discharge voltages, $U_d$. We find a positive effect of $U_d$ on filtration efficiency and ozone production. When enhancing $U_d$ from 0 to 6 kV, the filtration efficiency increases from 4.3% to 65.8% and the ozone production increases from 0.1 to 3.4 ppb. When further enhancing $U_d$ to 8 kV, the filtration efficiency increases to 90.3% and produces 11.6 ppb ozone (below the standard of 47 ppb limit [51]). However, the filtration efficiency is not significantly increased (0.9%) by enhancing $U_d$ further to 9 kV, while more ozone produces (17.1 ppb, as shown in Fig. 8a) and more power consumes (increases 33.3%, as shown in Supplementary Fig. S5). So we select $U_d = 8$ kV to further evaluate the influence of the polarizing voltages. Fig. 8b adds the filtration efficiencies for larger particles, which show the similar trend as for 0.3–0.5 μm particles.

Fig. 8c shows the single-pass filtration efficiencies for 0.3–0.5 μm particles with polarization voltage $U_p = 0$–20 kV and discharging voltage $U_d = 8$ kV. The external polarizing electric field boosts the filtration efficiency from 90.3% to 94.4% when applying a 15 kV $U_p$ (equivalent to 5 kV/cm electric field) to the polarization module. When $U_p$ increases to 20 kV, the efficiency is negligibly enhanced to 94.5%. As Fig. 8d shows, filtration efficiencies increase to a higher level for larger particles, because an external electric field can polarize both fibers and particles, strengthen the electrical force between fibers and particles, and enhance the electrostatic filtration efficiency. In summary, applied with optimal charging and polarizing voltages ($U_d = 8$ kV, $U_p = 15$ kV), the 45°-folded module reaches 94.4% filtration efficiency for 0.3–0.5 μm particles and 94.7% for submicron (0.3–1 μm) particles.

4. Conclusion

In this work, we developed three polarization modules with different folding angles ($\theta = 30^\circ$, 45° and 60°) for EAA coarse filtration. We compared the folded modules with the unfold module ($\theta = 180^\circ$) in filtration efficiency, pressure drop, QF, CQF and electrical field distribution. The following conclusions can be drawn:

1. The pressure drop of the EAA coarse filter module significantly reduces by folding filters from 180° (unfold, 16.1 Pa at 1 m/s) to 45° (5.9 Pa). However, due to the structural effect of the polarizing electrodes, a smaller folding angle ($\theta = 30^\circ$) hardly reduces the pressure drop (5.4 Pa).

2. The influence of $\theta$ on filtration efficiency is via the filtering velocity $u$ and the effective polarizing areas. By reducing $\theta$, $u = v_{air}\sin(0.5\theta)$ reduces and the mechanical filtration efficiency increases. Meanwhile, by reducing $\theta$, the effective polarizing area reduces as visualized by electric field simulation which reduces the electrostatic filtration efficiency. Taken together, the 30°-folded module achieves the highest filtration efficiency at 1 m/s air duct velocity ($\eta_{air}$), while the 45°-folded module achieves the highest filtration efficiency at larger $v_{air}$ of 1.5–3 m/s. A comprehensive modeling including the fluid-electric field coupling effect would be helpful to develop a deeper understanding of the mechanism.

3. On account of low pressure drop and high filtration efficiency at large air duct velocity (1.5–3 m/s), the 45°-folded filter achieves the highest QF and CQF, indicating the best comprehensive performance among all folded modules for application in HVAC systems. At as large air duct velocity as 3 m/s, the 45°-folded filter designed in this study maintains as low as 26.4 Pa, compared with 81.3 Pa of the unfold filter. Moreover, the 45°-folded filter significantly enhances the single-pass filtration efficiency for 0.3–0.5 μm particles from 80.3% (unfold) to 85.0%, and 81.1% to 85.5% for submicron (0.3–1 μm) particles. At lower air duct velocity (1 m/s), the 45°-folded filter shows higher filtration efficiency (94.7%) for 0.3–1 μm particles, and lower pressure drop (5.9 Pa). Even applied with high voltages, the 45°-folded module produces acceptable 11.4 ppb ozone, which meets the requirements of national standards.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seppur.2022.120631.

References


