Adhesion Force Analysis for Prevention of Particle Resuspension in Multiplexed Inertial Coalescence Filters

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Abstract

Fine airborne particles (< 10 μm) pose challenges for engineered systems, human health, and environmental pollution. This work investigates the relative influences of van der Waals and capillary adhesion forces during filtration to guide the design of multiplexed inertial coalescence filters, which are constructed with a parallel series of helical passageways designed for low pressure drop (<150 Pa) and capture of fine particulate matter (5–50 μm). Specifically, we experimentally quantified the influence of particle adhesion forces on filtration efficiency for capture of 6.1 μm activated carbon particle clusters. Filtration efficiency for dry filters, where van der Waals adhesion forces dominate, is significantly diminished beyond a threshold flowrate due to the Saffman lift force, which causes wall-bound particle clusters to detach from the interior filter surfaces. For wetted filters, the capillary adhesion force is orders of magnitude greater than the Saffman lift force, and consequently the filtration efficiency is not adversely affected. We developed models for filter pressure drop and filtration efficiency accounting for the influence of particle adhesion forces; these models showed good agreement with experimental results. Filter quality factor was determined for varying particle sizes and flowrates and can be used as a design guideline for use-case-specific filter optimization, which is enabled by the customizable additive manufacturing approach used to fabricate the filters. Due to its versatility and low-pressure-drop nature, this filtration approach could find use in heating, ventilation, and air conditioning (HVAC), large particle and dust filtration in industrial processes, cleanroom pre-filtration, and beyond.

1. Introduction

Fine solid particles and liquid droplets suspended in air are ubiquitous in everyday life. Many engineered systems require separation of particles from process air streams, including for lunar dust filtration in space (Linnarsson et al. 2012; R. M. Rasheed and Weislogel 2019a; 2019b; R. M. Rasheed et al. 2020; R. Rasheed 2019), emissions control (Li et al. 2013; Eisen et al. 2001; Quiros et al. 2014), large particle filtration in industrial processes (Jaworek et al. 2021; Yu et al. 2020), particle filtration in construction (Sung, Yoo, and Kim 2021; Zhang et al. 2023), and pre-filtration for large particles in cleanrooms (Ebert et al. 1997; Sikka and Mondal 2022; Mukhopadhyay 2014). Meanwhile, transmission of droplets can be detrimental to human health (Ju et al. 2021; Lohmann and Feichter 2005), for example via the spread of pathogen-laden respiratory droplets in air (Tcharkhtchi et al. 2021; Jones and Brosseau 2015; Bourouiba 2020; Bahl et al. 2020). Commercial filtration methods typically involve nonwoven fiber-based membranes, such as those in commercial surgical and N-95 masks (Sundarrajan et al. 2014; Shao et al. 2022; Kadam, Wang, and Padhye 2018; Xu et al. 2016; Ogbuoji, Zaky, and Escobar 2021) and pleated mechanical air filters including high-efficiency particulate air (HEPA) filters (Azimi and Stephens 2013; Thomas et al. 1999; Sinclair 1976; Bluyssen, Ortiz, and Zhang 2021; Dubey, Rohra, and Taneja 2021), among others (Konda et al. 2020; Sheridan et al. 2005; Z. Feng and Cao 2019; Moosmüller, Chakrabarty, and Arnott 2009). Existing filtration methods, however, suffer from either (i) high pressure drops and, consequently, large energy consumption (Raynor and Leith 2000), (ii) reliance on moving components (R. M. Rasheed et al. 2022), or (iii) stability issues during extended use (Cortes and Gil 2007; Smith 1962).

In prior work, additively manufactured inertial coalescence filters (R. M. Rasheed et al. 2022) were developed to overcome these issues by leveraging the centrifugal forces experienced by flow in helical pathways (Fig. 1a); these filters improved on the state of the art as a low-pressure-drop, passive method for high-efficiency droplet filtration. Liquid droplet capture was investigated in prior work on these filters, where capillary forces resulted in complete capture of droplets that made contact with the filter surfaces. Solid particles, on the other hand, adhere via either capillary forces (on wet surfaces) or weaker van der Waals forces (on dry surfaces), impacting filtration performance. Indeed, adhesion of particles on surfaces has important implications for the performance of heat exchangers (Cho et al. 2017; Miljkovic et al. 2013; Awais and Bhuiyan 2019), self-cleaning of superhydrophobic surfaces (Quan et al. 2016; R. Raj et al. 2012), photovoltaic modules in solar panels (Gupta et al. 2019; Isaifan et al. 2019; Ilse et al. 2018; Chanchangi et al. 2020), and other relevant engineered systems (Suman et al. 2021; Kurz and Brun 2012), providing a body of literature to build on. In many of these aforementioned applications, particle filtration may be employed as a means of improving system performance, and enhancing system lifetimes. In this work, we expand upon prior work by investigating the utility of additively manufactured inertial coalescence filters for capture of solid particles. We quantified the van der Waals and capillary adhesion forces as well as the Saffman lift force acting on wall-bound particle clusters. We then assessed the competing contributions of the Saffman lift force and particle adhesion forces on the filter capture efficiency and filter quality factor to guide filter analysis and design for a range of applications.

2. Materials and methods

2.1 Filter manufacturing

We manufactured the multiplexed inertial coalescence filters from polylactic acid (PLA) using a fused deposition modeling (FDM) additive manufacturing process with three key length-scales:

(i) centimeter-scale filters are manufactured with (ii) a highly parallelized array of millimeter-scale helical paths (Fig. 1a) and are made of (iii) stacked layers of orthogonal lines of filament which produce a micrometer-scale porous medium with a void fraction of 40% (Fig. 1d). Additive manufacturing was used to enable the intricate internal helical geometries and multiple filter length-scales, and for versatility in allowing adjustments to filter parameters for performance optimization (Choi et al. 2020; Moridi et al. 2020). The filters were manufactured with individual helical paths arranged in triple helixes and repeated in hexagonally arranged cells to produce a complete filter (Fig. 1d). We investigated two filter designs: "filter A" with helix pipe diameter d_h = 2 mm, helix coil diameter d_c = 5 mm, and filter thickness L = 10 mm; and "filter B" with d_h = 3 mm, d_c = 6 mm, and L = 10 mm. Overall filter dimensions were maintained at 82 mm × 82 mm × 10 mm. The use of a hexagonal packing pattern resulted in a high density of flow passages per unit area (4.7 helixes/cm^2 for filter A and 3.0 helixes/cm^2 for filter B), which enabled efficient particle cluster filtration while maintaining filter structural integrity.

2.2 Filter performance characterization

We evaluated the performance of dry and wet filters to investigate the effects of van der Waals and capillary adhesion forces, respectively, on filtration performance. Specifically, we experimentally determined particle capture efficiency for 6.1 ± 1.5 μm activated carbon particle clusters and pressure drop across the filters at varying flow rates for the dry and wet cases in an experimental setup shown in Fig. 2. The size and morphology of the activated carbon particle clusters were determined using scanning electron microscopy images, shown in Fig. S7 in the Supplementary Materials document. The selection of 6.1 μm activated carbon particle clusters was based on their size, which is well-suited for studying both the inertial separation mechanisms of multiplexed inertial coalescence filters and the adhesion forces binding the particles to the filter surfaces. This size offers the necessary sensitivity to assess filter capture efficiency and particle adhesion. In addition, the particles are readily available commercially. The experimental apparatus consists of a fan, a converging inlet duct, and a square outlet duct. The base of our setup has a width W_1 = 139 mm, height H_1 = 80 mm and depth 109 mm. The inlet converging section also has a width W_1 = 139 mm, depth 109 mm, and height H_2 = 102 mm. The square outlet section has a width W_2 = 82 mm and height H_3 = 115 mm. At the end of the converging duct, a multiplexed inertial coalescence filter was installed. Pressure taps were inserted 1/2 inch from the inlet and outlet of the filter for pressure drop measurements. A Veris Industries T-VER-PXU-L differential pressure transmitter was used for measuring pressure drop across the filters during experiments, and a Mechatronics MS9238H24B fan was used for generating airflow in the experiments. An Omega FMA 1000 Series hot wire anemometer was used for velocity measurements. Activated carbon particle clusters with an average size of 6.1 ± 1.5 μm were used. The activated carbon particle clusters were introduced into the test section using a light airflow of lab air aimed at a large dish of activated carbon to disperse the particle clusters in the test section (shown in Fig. 2).

2.2.1 Dry filter characterization

The mass of a dry porous multiplexed inertial coalescence filter, such as the one shown in Fig. 1d of the main text, was measured before each experiment. The dry filter of known mass was installed in the experimental apparatus, shown in Fig. 2. Air was pulled through the experimental apparatus and activated carbon particle clusters were injected into the test section at a rate of 6.5 ± 4.5 mg/s by initiating a light air flow of lab air onto the large dish of 6.1 μm activated carbon particles. The settling time for the 6 μm particle clusters is on the order of tens of minutes, which is much greater than experimental residence times of the particle clusters in the test section (Utrup and Frey 2004). After an elapsed time, between 2-5 minutes, the experiment was stopped, and mass measurements of the filter after the experiment and the total dispensed mass of particles were recorded. The change in the mass of the multiplexed inertial coalescence filters and total mass of dispensed particles during the experiment were used to determine the capture efficiency of the filters.

2.2.2 Wetted filter characterization

As in the case of the dry filter capture efficiency characterization, the mass of a dry porous multiplexed inertial coalescence filter was measured before each experiment. The filters were then soaked in water for 1–2 minutes to fill the filter porous medium (but not the helical pathways) with water. The wetted filter was then installed in the experimental apparatus. As in the case of the dry filters, air was pulled through the experimental apparatus and 6.1 μm activated carbon particle clusters were injected upstream at a rate of 6.5 ± 4.5 mg/s of the test section by initiating a light air flow of lab air onto the large dish of carbon particles. After an elapsed time, between 2-5 minutes, the experiment was stopped. The wetted filter with captured particles was then baked in an oven at 90 ºC for 3 hours to remove the water from filter medium. Mass measurements of the dried filters with loaded particle mass and the total dispensed mass of particles in the test section were recorded. Mass measurements of the multiplexed inertial coalescence filter and total mass of dispensed particles during the experiment were used to determine the capture efficiency of the filters.

Figure 1

To assess the effects of filter soaking followed by filter drying on the mass readings in our experiments, multiplexed inertial coalescence filters were soaked in water and were then baked in an oven at 90 ºC for 3 hours to remove the water from the wetted filters. The change in filter mass due to particle cluster capture during a typical experiment was compared to the change in mass of the filters from the soaking and drying process in the absence of particles. Changes in filter mass suggest that mass gained due to left-over residue from water is ~100–200 times less than the captured particle mass in a typical experiment, and therefore has a negligible effect on filter capture efficiency results.

Figure 2

Table 1

2.3 Particle force analysis

2.3.1 Filter particle cluster capture efficiency with full particle cluster retention

In our previous work (R. M. Rasheed et al. 2022), we developed a theoretical model to predict capture efficiency and pressure drop for the multiplexed inertial coalescence filters, which we modify here for particle filtration. We model the particle clusters as ideal spheres. In our prior model, the filter particle cluster capture efficiency depends on the effectiveness of two inertial separation mechanisms. As illustrated in Fig. S1, particle clusters either hit the filter face directly or follow gas streamlines into the helical pathways where they are centrifugally separated from the air stream. The overall filter capture efficiency, $\eta = \eta_{\mathrm{f}} + \eta_{\mathrm{h}}(1 - \eta_{\mathrm{f}})$, combines contributions from both mechanisms in series, where η_{f} and η_{h} are the filter face and helical pathway capture efficiencies, respectively. Particle clusters entering the helical pathways experience centrifugal forces, causing them to migrate towards the outer walls, where they impact and are captured, as shown in Fig. 1a and Fig. S2. Details of the individual contributions to the overall capture efficiency can be found in the Supplementary Materials. However, this overall efficiency expression assumes that the captured particle clusters remain held on the filter permanently, which is not necessarily the case for solid particle clusters, which may be pulled off the filter surfaces under certain flow conditions.

2.3.2 Saffman lift force and adhesion force analysis on wall-bound particle clusters

Wall-bound solid particle clusters are held in place either by van der Waals forces (dry filters) or capillary adhesion forces (wet filters), shown in Fig. 1b. For small particle clusters (< 50 μm), van der Waals forces and electrostatic forces (Rajupet et al. 2022; Adamczyk and Warszyński 1996) are two ubiquitous forms of particle adhesion to filters. Naturally occurring electrostatic forces arising from net charges on particles are typically orders of magnitude smaller than van der Waals forces and are often neglected. Van der Waals forces, which occur between neutrally charged particles, arise from temporary dipole moments in molecules and atoms, and are the dominant adhesion force for non-conductive particles and surfaces, especially for small particles (< 20 μm) (Momin, Tucker, and Das 2018; Sharma and Setia 2019; Bowling 1985; J. Q. Feng and Hays 2003; Rajupet et al. 2021). Capillary adhesion forces formed by liquid bridges between particles and filter surfaces represent another important adhesion force in filtration (Matteson and Orr 1987; Rabinovich et al. 2002; Butt and Kappl 2009; Kralchevsky and Denkov 2001). While both van der Waals and capillary adhesion forces are relevant, capillary forces have been found to be at least an order of magnitude greater than van der Waals forces for particles smaller than 100 μm (You and Wan 2013; Drummond and Chan 1997; Fichet et al. 2007).

We assume the flow in the helical pathways to be a plug flow (discussed in detail in the Supplementary Materials). A steep velocity gradient near the wall generates a Saffman lift force on wall-bound particle clusters. The velocity gradient is relevant only on a very small length-scale close to the wall (~10–22 μm) and has important implications for wall-bound particle clusters but does not impact the overall assumption of a plug flow in the helical pathways, which have a diameter at least 100× larger than the boundary layer thickness. Centrifugal forces are orders of magnitude greater than those of the Saffman and Magnus lift forces for particle clusters that are in flight (i.e., not wall-bound). In addition, as particle clusters traverse the boundary layer near the walls of helical pathways, particle cluster deceleration due to the Saffman lift force and Stokes drag is found to be negligible, which means that particle clusters driven by centrifugal forces will always impact the filter walls. Once particle clusters are wall-bound, we assess whether they will stay adhered or will be dislodged from the surface by quantifying the Saffman lift force (Saffman 1965), which is determined by:

$$F_{\mathrm{lift}}(x) = 1.615(\rho_{\mathrm{a}}\mu_{\mathrm{a}})^{1/2} d_{\mathrm{p}}^{2}\left(\bar{u}_{\mathrm{p}} - u_{\mathrm{p}}\right)\left|\frac{\partial u}{\partial r}\right|^{1/2} \operatorname{sgn}\left(\frac{\partial u}{\partial r}\right), \tag{1}$$

where d_{p} is the particle cluster diameter, ρ_{a} and μ_{a} are the airflow density and dynamic viscosity, respectively, u_{p} is the particle cluster velocity ($u_{\mathrm{p}} = 0$ because the particle cluster is stationary), and $\bar{u}_{\mathrm{p}}$ is the average airflow velocity at the particle cluster centerline. The Saffman lift force is a function of helix axial position along the length of the helical pathway, x, shown in Fig. 1c and Fig. S3a, which is due to the dependence of F_{lift} on the magnitude of the velocity gradient near the wall, which in turn is dependent on wall shear forces that are themselves dependent on x. The Saffman lift force is determined by approximating the average airflow velocity at the particle cluster centerline using, $\bar{u}_{\mathrm{p}} = 0.5 d_{\mathrm{p}}\, du/dr$, and approximating the velocity gradient from the wall shear force in the helical pathways, determined using Eq. (S9):

$$F_{\mathrm{lift}}(x) = 0.0357\mu_{\mathrm{a}}^{-1}\rho_{\mathrm{a}}^{2} d_{\mathrm{p}}^{3}\bar{u}^{3} f_{\mathrm{a}}(x)^{3/2}, \tag{2}$$

where and f_a is a modified friction factor for developing laminar flows from Ghajar (2019), which is adapted from the work of Shah (1978). The Saffman lift force is orthogonal to the filter surface and is opposed by an adhesion force on the particle clusters. For the dry filter case, the van der Waals force is the dominant adhesion force between the filter surfaces and the 6.1 μm activated carbon particle clusters (Krupp and Sperling 1966). The particle clusters can be treated as residing on a flat surface (shown in Fig. 1b) because $d_p/d_h << 1$ for all relevant filter geometries. This simplification allows us to determine the van der Waals force between a particle cluster and the filter surface by:

$$F_{\mathrm{vdW}} = -\frac{A_{\mathrm{cp}} d_{\mathrm{p}}}{12\Delta y^2}, \tag{3}$$

where A_{cp} is the Hamaker constant between activated carbon and the surface of our filter material and is determined by $A_{\mathrm{cp}} = \sqrt{A_{\mathrm{c}} A_{\mathrm{p}}}$, where A_c and A_p are the Hamaker constants for carbon (Maurer, Mersmann, and Peukert 2001; Morra, Occhiello, and Garbassi 1992) and plastic (G. Raj et al. 2009; Wang et al. 2015), respectively. The Lennard-Jones potential is used to approximate Δy, the minimum distance between a carbon particle cluster and the filter surface, and is found to be $\Delta y = 2^{1/6}\sigma$, where σ is the van der Waals radius. Details on the Lennard-Jones potential as well as the effects of surface roughness on the van der Waals force (Kumar, Staedler, and Jiang 2013; Kim et al. 2016; Tormoen, Drelich, and Nalaskowski 2005; Ramakrishna et al. 2011) are provided in the Supplementary Materials. We define a particle cluster escape zone in each helical pathway from $x = 0$, where F_{lift} approaches infinity, to $x = L_e$, the point where $F_{lift} = F_{vdW}$, as shown in Fig. 1c and Fig. S3a. Wall-bound particle clusters will be liberated from the walls in this escape zone where $F_{lift} > F_{vdW}$. For helix axial position $x > L_e$, F_{vdW} dominates over F_{lift}, and particle clusters remain wall-bound. We define a ratio between the escape length, L_e, and the total helical pathway length, L_{helix}, to characterize the fraction of the filter pathway that does not contribute to capture of particle clusters, which we call the capture efficiency correction:

$$\eta_{\text{c}} = 1 - \frac{L_{\text{e}}}{L_{\text{helix}}}. \tag{4}$$

Plots of the capture efficiency correction for filters A and B as a function of inlet flowrate are shown in Fig. S3b. The capture efficiency correction from Eq. (4) is used to compute a modified filter capture efficiency:

$$\eta_{\text{m}} = \eta_{\text{f}} + \eta_{\text{h}}\eta_{\text{c}}(1 - \eta_{\text{f}}). \tag{5}$$

When $L_{\text{e}} << 1$, for example at low inlet flowrates, $F_{\text{vdW}} > F_{\text{lift}}$ across nearly the entire axial length of the helical path except for a negligibly small region near $x = 0$. In the case where $L_{\text{e}} << 1$, the capture efficiency correction has a value of 1, and Eq. (5) simplifies to the overall filter capture efficiency defined in prior work (R. M. Rasheed et al. 2022).

When the filters are wetted, capillary forces represent the dominant adhesion forces between particle clusters and filter surfaces, as shown in Fig. 1b. A liquid bridge forms between each wall-bound particle cluster and the filter surface and holds the particle cluster in place. The capillary adhesion force, or the force required to break the liquid bridge adhering the particle cluster to the filter surface, is approximated as:

$$F_{\text{cap}} = \pi d_p \gamma \cos\theta , \tag{6}$$

where γ is the liquid surface tension (water in this work) and θ is the contact angle between activated carbon and water (Jaffe et al. 2004; Marković et al. 1999; Hummer, Rasaiah, and Noworyta 2001). The capillary adhesion force, F_{cap}, is shown in Fig. S4 and is on the order of 200 nN for the 6.1 μm activated carbon particle clusters. For all filter geometries and inlet flow conditions of interest, $L_e << 1$ in the capillary adhesion case because $F_{cap} > F_{lift}$ for nearly the entire axial length of the helical flow paths, which means the wetted filter capture efficiency can be predicted using the ideal capture efficiency model developed in prior work, where $\eta_c = 1$. We also developed a theoretical model for filter pressure drop, detailed in the Supplementary Materials.

3. Results and discussion

3.1 Filter particle cluster capture efficiency

Capture efficiency results are shown in Fig. 3 for 6.1 μm activated carbon particle clusters versus inlet flowrate for filters A (Fig. 3a) and B (Fig. 3b) for both dry and wet filters. For both filters, the filter capture efficiency is a strong function of flowrate. In general, larger flowrates result in larger inertial forces and larger net filter capture efficiency. For the dry filters, however, the filter capture efficiency starts to decline rapidly past a threshold flowrate, which we define where the particle cluster escape length L_e exceeds 1% of L_{helix} ($Q > 1800$ cm^3/s for filter A and $Q > 3200$ cm^3/s for filter B). As flowrate increases, the Saffman lift force on particle clusters also increases, resulting in $F_{lift} > F_{vdw}$ over larger regions of the helical pathways in the dry filters, increasing L_e and reducing the overall filter capture efficiency. The modified capture efficiency model from Eq. (5) predicts the trend and magnitude of the dry filter capture efficiency well, especially at high flowrates ($Q > 3000$ cm^3/s). The wet filters do not show any significant reduction in filter capture efficiency as flowrate increases, and the predictions from the ideal capture model predict the capture efficiency with reasonable accuracy. These results suggest that the wetted filters maintain adhesion of the captured particle clusters in the helical pathways, which verifies that $L_e << 1$ in the wetted filters due to the large magnitude of F_{cap}. To further validate our theoretical model, we also determine filter capture efficiency as a function of inlet flowrate for 7.75 μm monodisperse silica particles. Results are shown in Fig. S9 of the Supplementary Materials document and show good agreement between experimental and model results.

Figure 3

3.2 Filter pressure drop

Filter pressure drop as a function of inlet flowrate was also determined for dry and wet filters, shown in Fig. 4. The filter pressure drop is a strong function of flowrate, but we note that we can routinely perform filtration at less than 150 Pa. Wetted filters in general have larger pressure drops, which is due to swelling of the PLA materials used to construct the filters. In prior work, PLA has been shown to swell by 2–10% (Kukkonen, Ervasti, and Laitinen 2022; Tee et al. 2017; Guo et al. 2017), which in our case results in smaller helical pathways and a higher velocity per pathway, in turn increasing pressure drop. The pressure drop for filter B is generally smaller than filter A, which is a result of larger helical flow pathways. We developed a theoretical model for the filter pressure drop in the Supplementary Materials, Eq. (S19), that predicts the trend and magnitude of the experimental filter pressure drop well.

3.3 Filter performance optimization

Figure 5a shows a plot of capture efficiency ratio between wetted and dry states for filters A and B as a function of inlet flowrate, with an inset of filter escape length as a function of inlet flowrate. The efficiency ratio is unity up to a threshold flowrate ($Q < 1800$ cm^3/s for filter A and $Q < 3200$ cm^3/s for filter B) defined by $L_e = 0.01(L_{helix})$. For applications where capture efficiency is the most important parameter, wetted filters generally perform better than dry filters. Wetted filters, however, will lose liquid in the porous medium due to evaporation. We propose using a liquid droplet spray to replenish the liquid in the filter medium at a rate that is equal to the losses from the filter medium, as shown in Fig. S6. In some applications, water may be substituted by a low vapor pressure liquid, such as oil, to reduce losses of the liquid through mass transfer. Although dry filters have diminished capture efficiency compared to wet filters, dry filters operate with a lower pressure drop. Larger capture efficiency is generally desired, but usually requires higher filter pressure drop and, and consequently, a higher energy consumption. To quantify the overall filtration performance, filter quality factor (QF) has been adopted in the literature, where $QF = -\ln(1-\eta)/\Delta p$. Figure 5b shows QF ratio between dry and wet filters for filter A for varying particle diameters and inlet flowrates. Results in Fig. 5b are determined from model predictions for the filter quality factor ratios. In general, wetted filters are desirable ($QF_{\mathrm{wet}}/QF_{\mathrm{dry}} > 1$) when flowrates are high ($Q > 2000$ cm^3/s) and when the particle diameter is small ($d_{\mathrm{d}} < 9$ μm). $QF_{\mathrm{wet}}/QF_{\mathrm{dry}} < 1$ when particle diameter is large ($d_{\mathrm{d}} > 10$ μm) due to lower filter pressure drop for the dry filters. QF informs filter design optimization for various applications for varying particle sizes and flowrates, which is enabled by the versatile additive manufacturing process used to manufacture the filters.

Figure 4

Figure 5

4. Conclusion

In summary, this work investigates the influence of van der Waals and capillary adhesion forces on filtration performance of multiplexed inertial coalescence filters and provides filter design guidelines considering the relevant adhesion forces. The theoretical investigation aided by experimental results of the various forces outlines the importance of increased particle adhesion force on filter surfaces to maintain filter capture efficiency for flows with high flowrates or for small particles ($d_{\mathrm{d}} < 9$ μm). The use of capillary adhesion, however, requires a wetted filter and can result in higher filter pressure drops, which in turn can reduce filter quality factor and reduce performance in some systems and applications. Furthermore, maintaining capillary adhesion forces may require replenishing the filter medium with a droplet spray or other means. Therefore, in some cases dry filters may be advantageous, especially for the capture of large particles ($d_d > 9$ μm) which exhibit relatively higher van der Waals adhesion forces, and also for low flowrate applications. This work has implications for numerous engineering applications including HVAC systems, development of life support systems, and heat exchangers.

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Disclosure statement

The authors declare the following financial interests which may be considered as potential competing interests: R.M.R and D.J.P have ownership stakes in the company Helix Earth Technologies Inc., a Delaware C corporation that is commercializing the technology detailed in this work and also pursuing intellectual property on the technology developed in this work.

Data availability statement

The data that support the findings of this study are available within the article and its supplementary material, which details development of the mathematical models, experimental methods, and droplet deployment methods: (Hyperlink to Supplementary Materials).

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Figures

Figure 1

Figure 1. *(a) The multiplexed inertial coalescence filter is made of a parallelized array of individual helical pathways that impart centrifugal forces on particle cluster streams, causing the particles to hit the outer walls. (b) Particle clusters adhere to the walls of the helical pathways via van der Waals forces (dry filters) or capillary forces (wet filters). (c) Dry filters lose captured particles due to the Saffman lift force exceeding the van der Waals adhesion force, while wet filters maintain captured particle clusters due to the much larger capillary adhesion force. (d) Photograph shows a filter (filter A: d_h = 2 mm, d_c = 5 mm, and L = 10 mm) showing the filter porous medium and triple helix packing.*

Figure 2

Figure 2. *Experimental setup with a multiplexed inertial coalescence filter in-line with a fan in a duct apparatus showing pressure gauges and activated carbon particle generator.*

Figure 3

Figure 3. *Capture efficiency versus inlet flowrate for dry and wet multiplexed inertial coalescence filters (a) A and (b) B. Data points are experimental values and solid curves are theoretical predictions with shaded regions representing model uncertainty.*

Figure 4

Figure 4. *Pressure drop versus inlet flowrate for dry and wet multiplexed inertial coalescence filters (a) A and (b) B. Data points are experimental values and solid curves are theoretical model predictions.*

Figure 5

Figure 5. *(a) Filter capture efficiency ratio between wetted and dry filters versus inlet flowrate for filters A and B for 6.1 μm activated carbon particles with inset figure showing escape length versus inlet flowrate for dry filters, and (b) curves of quality factor ratio between dry and wet filters as a function of particle diameter and inlet flowrate for filter A. Results are generated from models.*