INTRODUCTION

Particulate matter (PM) has been identified as a major health concern according to the World Health Organisation (WHO), in particular on cardiovascular and respiratory health.¹ The Lancet Commission on Pollution and Health highlighted 6.4 million premature deaths annually due to exposure to PM.² Exposure to PM has been shown to occur primarily indoors, and in particular in microenvironments of the home and workplace.³,⁴ Studies have reported that office workers, for example, spend over 90% of their time indoors each day.³

Air filtration systems containing air handling units (AHUs) are the primary method of removing PM from the ambient airflow into buildings and controlling indoor air quality. These filters are generally installed within the heating, ventilation and air conditioning systems (HVAC), which contains the AHU, ventilation ducts and other components. The EU directive on the energy performance of buildings identified building energy consumption as accounting for 40% of the total energy consumption within the EU.⁵ HVAC systems have been identified as a vital target area where significant reductions in energy consumption can be achieved. They account for 40%–50% of

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the energy consumption among non-domestic buildings. In particular, ventilation fans consume energy due to the system’s resistance which generates a pressure drop when achieving the desired flow rate. This occurs from air exchanges between the fresh air and indoor air. A consequence of the air filtration system is PM loading upon the filters, which increases the pressure drop in HVAC systems. Since the pressure drop is related to the energy consumption of the fan, this has an adverse effect on building energy efficiency.

This work examines the migration of PM from the ambient environment into the inlet of common commercially available ventilation systems that are typically installed on AHUs. Differences between ambient PM concentrations and those entering AHU inlets are quantified using the concept known as Aspiration Efficiency (AE). This concept is a measure of the transport of particles through an orifice between two fluid flows. The two fluid flows, in this case, are the ambient air and the ventilation flow, which are separated by the orifice of the AHU inlet. Previous investigations have examined the effectiveness of AHU inlets designed to achieve low values of AE resulting in lower concentrations of PM entering the ventilation system, with consequent improvements in indoor air quality and energy efficiency. Morgan et al. showed that an AHU inlet could be designed to passively reduce the concentration of PM entering the AHU by 34% using the AE concept (ie., taking advantage of particle inertia among other factors).

This paper is concerned with developing an understanding of the migration of ambient PM into the inlet of existing commercially available AHU inlets. By determining the AE of existing AHU inlet designs, we aim to establish the dynamics of PM concentrations passing from the ambient environment to indoor spaces. Understanding the particle dynamics of current systems is vital to identify means to reduce indoor air pollution and building energy consumption, through lowering of in-AHU particle concentrations and the pressure drop on HVAC filters. In the following sections, the design, grid development, and numerical modeling of the aforementioned problem are described. Computational fluid dynamics (CFD) is used to conduct this assessment, and the verification and validation of the CFD model used are presented herein, as well as the analysis of the dynamics of PM concentrations for three common commercially available AHU inlet designs.

### 2 ASPIRATION EFFICIENCY

Aspiration efficiency is the ratio of the concentration of particles (C) in the cross-sectional area of the inlet of an orifice to the concentration present in the undisturbed ambient air (C₀). This ratio is a measure of the efficiency with which particles are transported from the ambient environment into the orifice inlet. Inertial forces acting upon the particles can prevent some particles from following particular fluid streamlines which can result in an AE of less than 100%. The ratio is expressed as:

\[
AE = \frac{C}{C_0} \times 100
\]

Numerous studies have been conducted on the factors that influence the AE of air pollution sampling devices, both for thin and thick-walled probes. The thickness of the walls has a significant effect on aspiration efficiency with thin-walled probes achieving AE values closer to 100%. Thick-walled probes are more sensitive to secondary aspiration which occurs through rebounding, re-entrainment, and deposition. Secondary aspiration occurs through particle rebound and entrainment. Particles can potentially strike a surface and their interaction with the wall will depend on its inertial impaction (ie., either through fluid speed, particle diameter, or density). The particle will then become potentially resuspended in the fluid flow. While thin and thick-walled probes were investigated initially, the same theory has also been applied to analyzing the AE associated with the human mouth and nose. Various other environmental and design factors have been found to affect AE including Stokes number, the angle between the ambient wind and the plane of the orifice inlet (ie., yaw angle), gravitational settling, inlet geometry configuration, and velocity ratios. The velocity ratio (R) in Equation (2) is a dimensionless quantity expressing the ratio of ambient air velocity (U₀) to an orifice suction velocity (Uₛ):

\[
R = \frac{U_0}{U_s}
\]

The Stokes number in Equation (3) is also a dimensionless quantity describing the reaction of particles in fluid flow. It is the ratio of the characteristic response time of the particle to the characteristic response time of the fluid.

\[
St = \frac{d \rho_p U_0}{L_c \mu}
\]

\[
L_c = \frac{2ab}{a + b}
\]
Where \(d_p\) is the volume equivalent sphere diameter, \(\rho\) the particle density, \(\mu\) is fluid viscosity, and \(L_c\) is the characteristic length scale used for a rectangular duct. The variables \(a\) and \(b\) are the inlet side lengths at the interface between the AHU and the ambient environment. Particles with small Stokes numbers (i.e., \(St \ll 1\)) have quick response times to the fluid flow and will follow the fluid streamlines. Conversely, with larger Stokes number (\(St \gg 1\)) the effects of the turbulent fluctuations become negligible and the particle inertia dominates. To achieve an AE of 100%, isokinetic air sampling conditions are preferred. Isokinetic sampling requires that the ambient wind speed and sampling velocity are in equilibrium where the yaw angle (\(\alpha\)) is zero. Generally, these conditions are unachievable and anisokinetic sampling is prevalent where misalignment of the sampler with the oncoming wind (\(\alpha\neq0\)), subisokinetic condition (\(U_s>U_0\)), or superisokinetic conditions (\(U_s<U_0\)) can occur. Superisokinetic conditions generate AE efficiencies less than unity and subisokinetic conditions efficiencies tend to be greater than unity. Therefore, the magnitude of the ambient air and orifice sampling velocities have a significant effect on the AE for forward-facing sampling probes.

The Stokes numbers, velocity ratios, and yaw angle are intrinsically linked too, with regards to the AE of an air sampling device. The literature shows larger yaw angles tend to decrease the AE with a constant velocity ratio. The AE was also found to increase at yaw angles of \(0\leq\alpha\leq60^\circ\), as the velocity ratio increases. Larger Stokes numbers have greater particle inertia which delays its reaction for converging flows, especially at greater yaw angles. Conversely, as the velocity ratio decreases and \(\alpha \geq 90^\circ\), AE increases. Wen and Ingham (1995) demonstrated that a rear-facing (\(\alpha=180^\circ\)) thin-walled sampling probe caused a reduction in particles sampled with increasing ambient speed and decreasing suction velocity. The AE was also found for all orientations in various studies to approach 100% as the Stokes number went toward zero.

A large volume of literature exists upon the design of PM samplers considering AE. Recently, the AE concept has been reverse-engineered to intentionally reduce the AE of large aspirating systems (i.e., building ventilation system). McNabola et al. (2013) investigated the effect of designing a multiple blunt-nosed ventilation hood on a 1:4 scale prototype for a large aspirating system known as aspiration efficiency reducer (AER). This device was found to be effective at restricting the passage of PM into the ventilation inlet at various flow rates, PM diameters, yaw angles, and demonstrated the potential for significant energy savings. Morgan et al. (2017) developed a full-scale prototype AER and field-tested the device. This consisted of the comparison of a forward-facing AHU with a generic inlet design and a rear-facing AHU with an AER device attached at the inlet (relative to prevailing wind directions). The analysis consisted of examining the difference in PM diameter distributions and filter weights but no AE values were recorded. The results again showed the AER device was more efficient at reducing the concentrations of PM within the AHU. No studies are available in literature which examine the AE of existing conventional AHU inlets and the implications of this on indoor air quality and building energy consumption.

### 3 | METHODOLOGY

#### 3.1 | Computational domain

A 3D model of a building AHU was constructed using Solidworks and meshed in ANSYS 18.1. The model was constructed to simulate the geometry of a typical AHU sitting on the roof of a flat roof building. The AHU could be mounted at any orientation relative to ambient wind on a flat roof in practice, but based upon studies conducted by Wen & Ingham on aerosol samplers, the most pertinent positions for examination were found to be rear and forward-facing orientations. Therefore, a forward and rear-facing 3D AHU model was created where the latter is illustrated in Figure 1. The numerical model was based upon a real AHU with dimensions of 2.01 m (L) × 0.755 m (H) × 0.85 m (W) and an AHU filter inlet with a surface area of 0.36 m².

There is currently no literature available with recommended distance for flow over an AHU, but the flow dynamics are analogous to flow around a building. The upwind and top boundary were created at a distance of 5 H from the AHU. The lateral height of the domain was 3.5 H from the sides of the AHU wall to the domain boundary. Finally, the boundary downwind of the AHU was set to 10 H from the AHU. The upstream, downstream, lateral, and top boundaries of the computational domain were chosen based upon the recommendations of Tominaga et al. (2008) and correspond with the recommended blockage ratio of \(<3\%\).^{23,24}

Two different inlet configurations were created for testing in ANSYS FLUENT as shown in Figure 1B,C and are commercially available on the EU market but their exact information has not been included due to data sensitivity. Inlet 1 is a generic design typically installed on both ventilation fans and AHUs and contains a single large orifice. Inlet 1 is designed to prevent rain droplets from entering the AHU, and this is achieved by angling the inlet face downwards. The geometry of the Inlet 2 design has similar orientations to Inlet 1 but instead uses a louver design (i.e., \(\leq90^\circ\)) that has multiple and smaller orifices. Again the original purpose of the design is to prevent the ingress of rainfall which is achieved by the louver structure. The cross section of both inlets tested is shown in Figure 1B,C, and their corresponding dimensions can be found in Table 1. The comparison of Inlet 1 and Inlet 2 was intended to enable the comparison of the most commonly found AHU inlet geometries in practice. Several other variables were also investigated to determine their effect on AE for large aspirating systems. This includes the wind direction (\(\leq0^\circ\) and \(180^\circ\)) relative to the AHU which accounts for the orientation of the AHU. The wind speed ranged from 1 to 10 m/s. Typically, the flow rates of an AHU will vary depending upon the building demand throughout the day and will result in ventilation velocities of between 1 and 3 m/s (i.e., flow rate from 1296 to 3888 m³/hr).

The effect of the ventilation velocity and wind speeds was examined with Inlet 1 using a particle diameter of \(D_{2,5}\) as particles within this size range have been found to affect the health of human beings more adversely.
Finally, a comparison between the various inlet geometries was investigated using their corresponding Stokes numbers. Four different velocity ratios (R), with both yaw angle orientations, were tested which amounted to eight different case comparisons between Inlets 1 and 2. For each case, the Stokes number was varied by changing the particle diameter which ranged from $D = 2.5 \mu m$ to $D = 90 \mu m$, the ambient wind speed and the characteristic length which for Inlet 1 is 0.584 m and 0.38 m for Inlet 2. Ambient wind velocities of 1.5 m/s, 2.5 m/s, 5 m/s, and 7.5 m/s were used to vary both R and St. An AHU design flow rate of 3400 m$^3$/hr (ie., ventilation velocity 2.6 m/s) was used for each case and was based upon the AHU model tested by Morgan et al.\textsuperscript{10} The viscosity and density were held constant at 1.79E–05 kg/ms and 2 g/cm$^3$, respectively. The PM mass flow rate was also calibrated based upon an average wind speed of 6 m/s and a mean concentration of 7 µg/m$^3$ as described by Morgan et al.\textsuperscript{10} which was observed at roof level in Dublin City Centre, Ireland.

### 3.2 Boundary conditions and solver settings

As shown in Figure 1, the computational domain consisted of a pressure outlet, wall, symmetry, and a velocity inlet for the AHU inlet and ambient air. A uniform velocity profile was used at the freestream, and a suction velocity with varying magnitude was applied to the inlet behind the different AHU Inlet geometries. In general, the instantaneous velocity field is unknown and the SIMPLEC algorithm was used for the velocity-pressure coupling scheme. The gradients were evaluated using the Green-Gauss node-based method and the second-order pressure interpolation scheme was employed. Second-order upwind discretization schemes were used for the momentum, turbulent kinetic energy, and specific dissipation rate. An unsteady Reynolds-averaged Navier-Stokes equation (URANS) was chosen with a time step of 0.005 s, and temporal discretization was achieved with a bounded second-order implicit time integration method. Steady-state conditions for both PM concentrations and velocity were monitored. The ambient concentration of PM was monitored at both the ambient and AHU inlets, and a time-averaged sample was collected under steady-state conditions.

### 3.3 Numerical models

The airflow in the computational domain was considered to be incompressible, and turbulent flow was modeled using RANS $k$-$\omega$ shear-stress transport (SST) model.\textsuperscript{25} It is superior to the $k$-$\epsilon$ models in near-wall flow and produced similar results within freestream flow regions for particle deposition,\textsuperscript{26} flow around buildings,\textsuperscript{27} and ventilation of buildings.\textsuperscript{28} A full description of the numerical model can be found in Appendix B.

Particulate matter dispersion was simulated using the discrete phase model (DPM) method. DPM models solid particles through the specification of their concentrations, mass flow rates, diameters,
and shape factor. This method uses a Lagrangian reference frame and tracks the trajectories of the particles through the continuum fluid. The trajectory of a particle is resolved by integrating the force balance on the particle. The force balance in Equation (5) equates the particle inertia with external forces in a cartesian coordinate system expressed as:

$$\frac{du_i}{dt} = F_D(u_i - u_i^t) + \frac{\bar{g} \rho p - \rho}{\rho_p} + f_i$$  \hspace{1cm} (5)

Where $u_p$, $\rho_p$, $\bar{g}$, and $f_i$ are the fluid phase velocity, particle-phase velocity, acceleration due to gravity and additional forces respectively in the $i^{th}$ direction. The drag force ($F_D$) of a solid particle is dependent on the coefficient of drag where various formulations exist based upon the particle size and shape. The particle shape is defined through a shape factor that relates the surface area of a particle having an equivalent volume as the particle to the actual surface area of the particle. A shape factor of 0.4 was used to generate non-spherical particles and was calibrated against experimental data from Kenny et al. (1999), as described in Section 3.6.2. The shape factor in ANSYS FLUENT is related to the coefficient of drag through correlations developed by Haider and Levenspiel for non-spherical particles (1989).

The modeling of particles within the fluid flow must also account for their dispersion within the computational domain. A stochastic tracking method known as the discrete random walk (DRW) model was employed to compute the trajectory of a particle. This method predicts the particles path lines based upon turbulent diffusion within the fluid. DRW accounts for successive particle-eddy interactions based upon the initial conditions and locations. The prediction of the particle dispersion is therefore dependent on the integral time scale and the time spent in turbulent motion along the particle path. Thus, the eddies have a characteristic lifetime, length scale, and velocity scale. The end of said interaction between the eddy lifetime and the particle trajectory occurs when one of two criteria is achieved; the lifetime of the eddy expires or the particle crosses the eddy boundary.

### 3.4 | Verification and validation

#### 3.4.1 | 3.4.1 Grid independence test

A structured hexahedral grid was used upstream, downstream, and either side of the AHU with a cell size of 0.02 m. Unstructured hexahedral/tetrahedral cells were placed around the AHU with an inflow layer applied to the walls to achieve a $y^+$ approximately equal to one. The GCI method was used to estimate the ordered discretization error associated with CFD studies. GCI was derived from the generalized Richardson extrapolation method by Roache for the purpose of quantification of numerical uncertainty with regards to spatial and temporal discretization errors. The relative error of the grid independence test requires solutions to be acquired from three grids with different resolutions and the GCI in Equation (6) can be found from:

$$GCI = \frac{t_1 e_2}{r^p - 1}$$  \hspace{1cm} (6)

Where ($f_j$) is 1.25 as recommended by Roache for three or more grids, $e_j$ is the approximate relative error, $r$ is the grid refinement ratio, and $p$ is the order of accuracy (based upon second-order methods, theoretically $p = 2$). Three grids were tested with the coarse, medium, and fine grids having 900,184, 135,2830, and 218,2342 cells, respectively. The velocity predictions were sampled in the vicinity of ventilation Inlet 1, downstream, upstream, and above the AHU. The grid independence test sample locations were at $z/z_{ref} = 0.2$, 0.55, and 0.7, and a total of 120 points were taken for each grid. This accounted for the changing flow dynamics in each region. The results found that the fine grid was in excellent agreement with the extrapolated result as the maximum GCI was less than 6.5% and the discretization error was within acceptable limits.

#### 3.4.2 | Model validation

The first stage of model validation involved testing the mathematical models used for modeling the AHU against measured results by Kenny et al. (1999), which involved measuring the AE of personal inhalable samplers in low air movement environments. The physics involved in both tests were analogous to each other with the differences arising from the larger geometrical scale of the AHU compared to an air sampling device. This would provide a good indication of the validity of the current model as a wind tunnel test would also use a scaled-down physical model of an AHU that would be similar in size to a personal inhalable aerosol sampler. The model dimensions, boundary conditions, and grid arrangement are shown in Appendix A.

The CFD model and mean of Kenny’s experimental results were found to be in good agreement with an $R^2$ of 0.86 and a correlation coefficient of 0.98, as illustrated in Figure 2A. The error bars represent the standard deviation of experimental measurement, and all of the CFD samples were within these values. In addition, the linear correlation was examined where the CFD and experimental AE were assumed to be 0% when no PM concentration was present and was also resulted in a good agreement with an average error of 20%.

The results from the CFD model were also plotted against the spread of the Kenny data for comparison in Figure 2B. The numerical model predicted the AE of the smaller diameter particles very well as illustrated in Figure 2B and the discrepancy between the experimental and CFD results was primarily for particles with larger diameters. The AE of the 46 and 74 µm diameter particle concentrations resulted in the largest discrepancy between the CFD and experimental results. Although the deviation between the numerical results and experimental of 74 µm diameter particle AE were attributed to the number of tests conducted by Kenny et al. The experimental AE of
58 μm and 90 μm diameter particles was found to experience significantly lower minimum AE values than the 74 μm diameter particles. It would be reasonable to expect an increase in the size of the sample pool would have yielded a lower minimum AE of the 74 μm diameter particles.

Finally, the CFD model uses an equivalent volume method as described previously to determine the shape factor. This is not an exact physical representation of the particle shape but uses correlations to define the drag. As the shape factor was held constant, the error discrepancy associated with the larger particles became more significant as the particle drag increased with diameter.

4 | RESULTS

4.1 | Building HVAC operating conditions assessment for D_{2.5}

The effect upon AE of varying the ventilation flow for the AHU with Inlet 1 was assessed as the flow rate within a building HVAC system will change depending on the buildings fresh air supply demand. The magnitude of the corresponding suction velocity will influence the surrounding environments air flow field and has a significant impact on the concentrations of PM drawn into the ventilation system, as previous literature would suggest.

An analysis on the response of AE to the ventilation flow rates and ambient wind velocity is shown in Figure 3 for a forward-facing and rear-facing AHU relative to the wind direction. As the ventilation velocity of the AHU increased, there was typically a corresponding increase in AE for both a forward and rear-facing AHU. The exception being for the forward-facing AHU where only a negligible difference in AE was observed between ventilation velocities of 2–3 m/s. The results also show that there is little variation in AE as the ventilation velocity changed for a forward-facing AHU at low wind speeds.

The AE of the forward-facing AHU was found to increase as the ambient wind speed increases at a ventilation velocity of 2 and 3 m/s. This trend was not observed at a ventilation velocity of 1 m/s where there was no major discernible difference in AE across the wind speeds range tested. This suggests that the momentum at the AHU inlet was not large enough to induce particle rebound and entrainment conditions as opposed to the larger ventilation velocities where AE continually increased and eventually exceeded the ambient PM concentrations. Beyond 5 m/s in ambient wind speed, the difference in AE between the lowest and both larger flow rates becomes increasingly larger. At a wind speed of 10 m/s, there is approximately a 12% difference in AE at the lowest ventilation velocity in comparison to the highest.

The rear-facing AHU with Inlet 1 in Figure 3 was found to more effective at reducing PM concentrations in the ventilation system in comparison to its counterpart, the forward-facing AHU, even at the highest flow rate. Similarly, the rear-facing AHUs lowest flow rate was found to produce lower AE values than the higher flow rates at all wind speeds tested. The rear-facing configuration resulted in significantly different AE values and a higher variability about the mean AE compared to the forward-facing configuration. This was attributed to the turbulent conditions that forms around the AHU inlet which appears to have a major effect on the ambient PM concentration gradients.

When examining the rear-facing AHU at a constant ventilation velocity, results tended toward lower AE at mid to high ambient wind speeds in comparison to low wind speeds of 1–2 m/s where a large
increase in AE was observed. At wind speeds larger than 3 m/s, there was not a significant difference in AE values across their respective ambient wind speed range. This suggests that as the particle momentum increases, AE decreased, and a negative linear correlation was observed as illustrated in Figure 3.

The average AE was examined in Table 2 using the results from the wind velocity distribution in Figure 3 over the ambient wind velocity ranges of 1–10 m/s. The results show a large variation in the mean AE between ventilation velocities for the rear-facing AHU. It can be postulated that this is attributed to the variance of the data sets caused by the wake formation and momentum of the AHU inlet. Furthermore, a linear decrease in the average AE over the velocity range was observed for the rear-facing AHU. While no significant difference in the average AE was found when changing flow rates for a forward-facing AHU.

The results have shown that the orientation of the AHU with respect to ambient wind direction has a considerable effect on the AE. This is due to the sudden change of direction that the particle must undergo to be drawn into the ventilation system for the rear-facing AHU. Considering the ambient particle concentration of 20 µg/m³ used, the resulting mean concentrations in the forward and rear-facing AHUs ranged between 19 and 20 µg/m³ and 9.3–12.8 µg/m³, respectively, as taken from the results in Table 2. Differences in particle concentration of this kind in the AHU inlet are likely to have a significant impact on the loading rate of particulate matter on downstream filters, which in turn would greatly impact on building energy consumption. A limitation of this analysis lies in the fact that single diameter particle sizes were modeled using CFD here and are compared to concentrations of PM2.5 from the field which contains a range of particle sizes. A wider range of particle sizes are examined in the following section (2.5–90 µm).

### TABLE 2 Mean AE across ambient wind velocity range of 1–10 m/s

| Ventilation velocity | Forward-facing Inlet 1 | Rear-facing Inlet 1 |
|----------------------|------------------------|---------------------|
| 1 m/s                | 95.8%                  | 46.6%               |
| 2 m/s                | 99.6%                  | 58.1%               |
| 3 m/s                | 97.2%                  | 64.2%               |

### FIGURE 4 Variation of aspiration efficiency as a function of Stokes number for commercial AHU inlets where (A) \( R = 0.6 \) (B) \( R = 1 \) (C) \( R = 2 \) (D) \( R = 3 \) and an AHU flow rate of 3400 m³/hr

#### 4.2 Aspiration efficiency comparison of commercial AHU Inlets

An analysis of the two inlet configurations was conducted to investigate whether their different characteristics have any notable effect on AE, based upon their corresponding Stokes number as illustrated in Figure 4. The results showed that for both AHU inlets and the four wind speeds tested here, the rear-facing AHU is substantially more effective at reducing PM concentrations for all particle sizes in comparison to the forward-facing AHU.

Again, this was found to be the most important variable with regards to reducing AE and its effect is more discernible with both increasing particle size and ambient wind speed. As both the momentum and inertia of the particles become larger, the particles are more
likely to maintain their original trajectory and not that of the AHU fluid streamlines. Either increasing one variable or both will make it increasingly more difficult for the AHU inlet to draw in the particles. Therefore, as the particle momentum rises both through increased mass and faster wind speeds, AE was seen to decrease in Figure 4 with increasing St number. The resulting AE trendline tended toward zero for all the wind speeds tested for both rear-facing Inlet 1 and 2. For example at a wind speed of 5 m/s and 7.5 m/s where St >> 1, AE was found to be less than 1% as illustrated in Figure 4C,D. In the case of both lower wind speeds in Figure 4A,B, there was a continuous decrease in AE as the Stokes number increased.

Whereas the forward-facing AHU Inlet 1 typically recorded high similar AE values regardless of particle size and it was found that the geometry design had a major effect. In the case of Inlet 1 which incorporates a single large orifice and is more open to the atmosphere, there was not much variation in AE as the wind speed or particle diameter changes. Conversely the louvered model, Inlet 2, generated larger AE values when both wind speed and particle diameter increased. This occurred as the louvered wall surface area is greater in comparison to Inlet 1 and therefore more exposed to the oncoming wind. The particle motions will be largely dominated by the convective turbulent flow and inlet placement relative to the wind. Variation in particle concentration gradients within the fluid domain was generally affected by diffusion and convective transport throughout. Wall-bounded flow and areas with decreasing turbulence also generated conditions for turbophoresis of inertia-dominated particles. For example, the convective mass transport of PM of varying size into the AHU inlet will lead to greater impaction on the louvered walls. This creates conditions that are more susceptible to secondary aspiration through particle entrainment and rebound, especially with increasing particle diameter due to inertial impaction.

The variation in AE between both types of forward-facing AHUs was largely at higher Stoke numbers, and their differences were negligible at St << 1. The louvered model generated AE as high as 113% at a wind speed of 7.5 m/s and its highest St value, while Inlet 1 only incurred an AE of 76%. Considering that the rear-facing AHU Inlet 1 and 2 resulted in AE <1% at equivalent conditions, there would be a significant difference in the PM filter loading rate. Previous studies on the human mouth and nose, and on thin-walled aerosol samplers, have shown an averaged AE range between 20 and 105% across similar ambient wind speeds for particle diameters up to 100 μm. Where the forward-facing Inlet 2 outperformed, Inlet 1 with the same orientation was in the St range of 1–5 (ie., mid-sized particles and slower speeds). Instead, AE was reduced with decreasing wind speed and, in contrast with the AE of Inlet 1, resulted in very little variation in their respective trendlines and between particle sizes.

The results from Figure 5 illustrate the difference between rear-facing Inlet 1 and 2 with regards to AE, and their trendlines were not as dissimilar as the forward-facing AHUs. The rear-facing Inlet 2 at R = 0.6 was more efficient at reducing PM concentrations, as the St number increases. Although at the minimum St number, Inlet 1 was preferred. As the wind speed increased and R = 1, the rear-facing
Inlet 1 generated lower PM concentrations within the ventilation system. At the highest wind speed of $R = 2$ and $R = 3$, there was very little variation in the results between both inlets. Inlet 2 was found to be more efficient and approached zero at a lower St number. The variation in the profiles as R changes are due to the effect increasing wind speed has on particle momentum, in particular for the rear-facing configurations. Results from rear-facing AHU Inlet 1 of the D$_{90}$ particle AE are 27.5%, 22.4%, 0%, and 0% for 1.5 m/s, 2.5 m/s, 5 m/s, and 7.5 m/s, respectively. As particle momentum reduces, the particles are deposited closer to the AHU leading to higher AE. Similar observations can be drawn from the rear-facing Inlet 2 results as R changes.

In contrast, the forward-facing AHU variation in profiles is more dependent on particle momentum, which is greater near the AHU Inlet for this orientation due to the alignment of the velocity vectors and their impaction with the AHU inlet configuration walls. The forward-facing Inlet 1 is mostly open to the atmosphere with a single large orifice, the values are typically between 90 and 103%, which would be expected (ie. close to ambient concentration). A larger variation is seen with forward-facing Inlet 2 due to the aforementioned build up on their respective louver walls at high wind speeds. AE lowers with increasing St at low R values for Inlet 2 as the particle momentum is not high enough to generate significant impaction conditions and force the larger particles beyond the louvered inlets into the AHU. Again, the velocity ratio, R, has a major influence on AE due to its relationship with St through the effect of changing ambient wind velocity. Generally, there were only minor differences in AE between both inlets at the higher wind speeds and the inlet design was not as dominant as seen at the lower wind speeds.

The mean AE was examined in Table 3 at various R values and shows that for both the forward and rear-facing Inlets, Inlet 2 had the best performance levels overall. In particular, the rear-facing AHU Inlet 2 was particularly effective at $R = 0.6$ and $R = 3$ and the difference in AE from the R range 1–2 was small. This further signifies the importance of the orientation of the AHU with respect to the prevailing wind direction and the inlet geometry design on AE over a range of PM sizes and wind speeds. The main variation occurred with the forward-facing AHU’s datasets. AE increased linearly for Inlet 2 as R increased and was ranged from 75 to 102%. The forward-facing AHU inlet 2 was the only configuration that demonstrated this relationship, whereas both Inlet 1 orientations and the rear-facing Inlet 2 displayed a negative linear relationship between R and AE as shown in Table 3. Albeit, forward-facing Inlet 1 AE values were reasonably similar and only the slightest decrease in AE was observed as R increased and was ranged from 92 to 97%.

Considering a mean total PM concentration, $C_o$, of 20 µg/m$^3$ across a range of Stokes numbers (ie., 2.5–90 µm) within the ambient freestream air entering the model domain. At low ambient wind velocities (ie., $R = 0.6$), the mean total PM concentrations, C, between the commercial inlets would range between 15.2 and 19.4 µg/m$^3$ and 12.6–15 µg/m$^3$ for AHU inlet 1 and 2, respectively. This would result in a significant difference in the filter loading rate with a constant PM source emission. The ranges are different for each model due to the increasing variation in AE when R increases as shown in Table 3.

### TABLE 3 Mean AE across an equivalent aerodynamic particle range for commercial inlets 1 and 2 at a constant R value

| R   | Forward-facing inlet | Rear-facing inlet |
|-----|----------------------|-------------------|
|     | 1        | 2      | 1       | 2       |
| 0.6 | 97%      | 75%    | 76%     | 63%     |
| 1   | 94%      | 76%    | 49%     | 51%     |
| 2   | 92%      | 89%    | 32%     | 29%     |
| 3   | 92%      | 102%   | 29%     | 21%     |

5 | DISCUSSION

5.1 | Analysis of the flow fields around both commercial AHU Inlets

The numerical model was found to be effective at analyzing the PM dispersion over an AHU on a building rooftop. The AE of the various AHU configurations tested was found to be analogous to the characteristic performance of PM monitoring equipment published in previous investigations. Decreasing the ventilation velocity and/or increasing the ambient wind speed for a forward-facing AHU caused the impaction of the particles into the inlet generating higher AE at equivalent St values.

In the case of forward-facing AHUs for both inlets in Figure 5A,B, it can be seen that there is no variation in the vector orientations around the AHU inlet as the wind speed increases. The only noticeable effect is the change in magnitude of the velocity vector field around the AHU inlet. Inlet 1 is more open to atmosphere and both the trends illustrated in Figure 4 and the mean AE in Table 3, demonstrated the lack of variation in AE as R increased.

As shown previously, the performance of Inlet 2 was significantly different from Inlet 1. This was attributed to the dissimilar inlet designs. A rise in the AE of Inlet 2 was observed as the wind speed rose in comparison to Inlet 1 where AE was constant as St increased. This occurred as there was a large proportion of the particle laden wind flow being directed onto the walls on forward-facing Inlet 2 due to the louvered design as illustrated in Figure 5A,B, and this was the cause of secondary aspiration. This generated PM concentration within the ventilation system that was greater than the ambient PM concentrations. Whereas, Inlet 1 only had a single face that diverts the ambient flow into the inlet and over the AHU roof and did not provide conditions for secondary aspiration.

There is a significant variation in the ambient flow field dynamic for a rear-facing AHU for both Inlet 1 and 2 in comparison to the forward-facing AHUs, as shown in Figure 5. Inlet 1 at the
lower wind speed of 2.5 m/s generated an eddy upon the face of the Inlet geometry when the boundary layer detaches at the edge of the AHU body. As the wind speed increases to 7.5 m/s, no eddy formation occurred at this location due to increases in the momentum of the ambient wind forcing the fluid down the slope of the Inlet 1 walls.

In contrast, the flow field of Inlet 2 had a vector distribution similar for both speeds and is analogous to Inlet 1 at a wind speed of 7.5 m/s. The only variation is the point where the boundary layer reattaches in front of the AHU, with Inlet 1 reattaching the furthest from the inlet. The velocity vectors observed for a rear-facing AHU Inlet 2 in Figure 5A,B demonstrate a large proportion of the ambient flow being diverted into the louvered faces after boundary layer detachment. Smaller particle diameters are more susceptible to following the fluid streamlines, and this was attributed to the slightly higher AE observed in Figure 4 at low St numbers for both Inlets. Upon examination of the rear of the AHU on the forward-facing AHU, a large stagnant zone has formed. When the inlet is positioned here (ie., rear-facing AHU), the stagnant zone has been either eliminated or drastically reduced in scale and magnitude by the suction force of the AHU inlet.

A wind flow field analysis was also conducted on the mid plane of the AHU (ie., 0.5 h on ZX plane) as shown in Figure 6. At a wind speed of 2.5 m/s, there is very little variation between the forward-facing configurations, although the rear-facing AHU inlets when compared generate slightly different vector flow fields. The recirculation zones in front of Inlet 1 are larger than Inlet 2. This created a larger mixing zone around the AHU that led to higher mean PM concentrations being drawn into the AHU as shown in Table 3. In particular, the impact on AE becomes more noticeable as the St number increases. Whereas Inlet 2 has a smaller recirculation zone but with more intense circulation, the suction force of both inlet types also created stagnant zones on the side of AHU which did not occur in the forward-facing AHU’s. As the wind speed increased to 7.5 m/s, the flow dynamics are very similar but with a noticeable increase in the velocity magnitudes. The recirculation zones in front of the rear-facing AHU inlets have become larger. Yet the increase in particle momentum led to a decrease in potential for the particle trajectory to follow the ambient air streamlines. This was seen previously where the higher wind speeds for the rear-facing AHU were accompanied with lower AE for equivalent aerodynamic particle diameters.

Finally, Figures 5 and 6 demonstrated the variation in the flow patterns at both the interface between the ambient environment and inlet design, and near the AHU filter inlet. A small stagnant zone formed on the underside of Inlet 1 walls as boundary layer separation occurred through both a combination of the wind and AHU ventilation velocity. The results show the stagnant zone expanded in size as the wind velocity increased for both a forward and rear-facing AHU Inlet 1 configuration. Inlet 2 had a smaller internal compartment (ie., from AHU inlet to louvered faces and to AHU inlet) but multiple ports. Boundary layer separation is especially prominent for the forward-facing AHU inlet 2 as the wind comes into contact with the louvered faces and separates at the rear of each louver blade. The exception being the louvered blade located closest to the ground. This was attributed to the slightly different design to the other louver openings due to the flat base which also generated higher velocities at the environment/AHU interface. The stagnant zones are much larger for forward-facing AHU as the ventilation flow rate air vectors direction is more closely aligned with the oncoming wind increasing the speed of the flow over the walls of AHU Inlet 1 or 2.

**FIGURE 6** Wind flow field analysis (m/s) on ZX plane at 0.5 h of the both forward and rear-facing AHU at a wind speed of (A) 2.5 m/s (B) 7.5 m/s and an AHU flow rate of 3400 m3/h
5.2 | Commercial inlet design and AE concepts

The concept of AE has been previously used in the design and performance assessment of PM monitoring devices when an AE of 100% is desirable to ensure the quality of measurements. However, the reverse is most desirable (ie., AE of 0%) for a ventilation system. The design of each inlet examined here did not consider their impact on AE and subsequent concentration of particles entering the ventilation system, as their primary purpose is rain cover not air pollution control. However, each design was shown to induce differing AE values at different magnitudes of Stokes number. The inlets were quite different in their designs considering the difference in the number of orifices, orifice size, aerodynamic design, and inlet surface area. This implies that a combination of various AE concepts could be used to reduce the concentration of particles entering the ventilation system and consequently deposited on the filter or transported into the building. Inlet 2 was more effective at lower velocity ratios and for a rear-facing AHU. The particles had a sharper trajectory and the spread of the inlets from the ground to the roof of the AHU caused lower AE at higher St numbers. The larger particles will also tend to settle toward the ground where the single orifice is drawing a large volume of air from. Conversely at lower St values, Inlet 2 was less efficient at preventing the transportation of the particles into the ventilation system as there were more streamlines being directed onto the louvered face in comparison to the single face used by Inlet 1. This effectively stipulates potential design criteria for limiting the entry of small and large particles in the development of future commercial inlets designed with consideration of AE concepts. Furthermore, the results show significant scope for development of new AHU inlet designs that could respond to changes in wind direction. Considering the significant variation in AE between a rear and forward-facing AHU, irrespective of the inlet configuration, a novel PM control system for an AHU that responds to the wind direction could lead to substantial energy savings.

5.3 | Effect of PM filter loading on energy consumption

The built environment has been identified as a key consumer of energy across the world. The AE values found across a range of typical building operating and environmental conditions here have a major effect upon the ventilation fans energy consumption. The rate of PM loading upon the filter for the forward-facing AHU will reach saturation and consequently the maximum pressure drop over a much shorter interval of time as a result of the higher AE of its inlet. Therefore, the addition of a commercial inlet that reduces AE will provide several positive contributions to the operation of a building. There will be a reduction in the instantaneous PM filter loading, an increase in the filter lifespan and improved cleanliness of the indoor air by reducing PM concentrations within the ventilation system.

The energy costs and IAQ implications will depend upon the classification of filters being used (ie., its efficiency at removing PM of a specific size). Filters designed to have a higher capture rate of smaller particles will be susceptible to a faster saturation time due to smaller pores and the increased likelihood of trapping larger particles. Furthermore, PM characteristics will vary region to region depending on the particle size, distribution, concentration, and composition of anthropogenic and natural sources. Knowledge of the AE of the AHU being installed would allow designers to extrapolate the concentrations entering the AHU relative to field measurements within said ambient environment.

6 | CONCLUSION

A need for the development of next-generation commercial AHU inlets that are designed to reduce AE has been identified. The results from this study show a significant scope for a reduction in AE for large ventilation system as AE typically approached 100% for fine particles, especially at low ambient wind speeds. The orientation of the AHU is a major factor in the AE of the ventilation system and was found to be significantly lower for a rear-facing AHU. A linear decrease was observed in the average AE of the rear-facing AHUs for both configurations as the ambient wind speed increased. Whereas the forward-facing AHU inlet 1 showed no significant change as R increased and Inlet 2 experienced a linear increase in the average AE. Decreasing the AHU flow rate (ie., ventilation velocity) led to a significant reduction in AE at a constant wind speed for a rear-facing AHU but remained essentially unchanged for the forward-facing configuration. Furthermore, the results also showed a preference for an array configuration with smaller orifices and a louver design across a range of Stokes number.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.