Control of airborne particle concentrations in a meeting room with stand-alone air cleaners: influence of type, airflow rate, flow pattern and position in the room

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ABSTRACT

The objective of this study is to assess the ability to mitigate the airborne particle concentration in a mechanically ventilated meeting room with stand-alone air cleaners (ACs) as function of the amount and type of devices, the total airflow rate, the location(s) of the device(s) in the room and their flow pattern. Six commercially available ACs, selected to be representative of the French market, are included in the study, each featuring distinct airflow patterns for both air inlet and outlet. The intrinsic performances of the ACs have been measured according to the French standard (NF B 44-200, 2016). Their filtration efficiencies are close to 100%, as expected with HEPA filter, the airflow rates targeted for this study, 80, 200 and 400 m³/h corresponding to respectively 1, 2.5 and 5 volume per hour (vol/h), are attained. Nevertheless, the airflow rate is 20 to 50% lower than values declared by the manufacturers. The sound power level as well as the operating power of the air cleaners have also been measured.
Numerical 3D simulation (CFD) was used to assess 66 configurations of ACs in the room. The airflow pattern, the air velocity, the particle concentration as function of time and at different locations in the room at breathing zone were calculated. The cleaning efficiency represented by the particle concentration after 16 minutes AC operating divided by the initial concentration was determined. When the AC is placed in a corner behind a wall (a common placement), the performance is lower compared to other locations in the room. As the total airflow rate increases, the cleaning efficiency increases (C16/C0 decreases). The differences in particle concentrations across the room when an AC is used are weak at 5 vol/h but become larger at 2.5 vol/h. Airborne particle concentrations within the room are more homogeneous with the ceiling-type ACs. Also, most of the studied ACs have sound power levels exceeding 50 dB(A) above 200 m^3/h, which can lead to noise nuisance for occupants. 9 of the 66 simulated configurations were also assessed through experimental measurements of airborne particle concentrations using low-cost particle sensors (0.3 to 5 µm range).

KEYWORDS

Stand-alone air cleaner, performance, numerical simulation, measurement, indoor air quality

1 INTRODUCTION

In the industrialized countries, people spend most of their time indoors (at home, at work, at school, for shopping and in public transportation). They are exposed to various harmful airborne substances being in gaseous (CO_2, CO, VOCs, NO_x, etc.) or in particulate (fine particles) form. These airborne indoor pollutants come from indoors and outdoors and their level mainly depends on the air change rate, people and indoors activities. The use of stand-alone air cleaners (ACs) can mitigate the exposure of people to airborne indoor pollutants if the buildings where they live, or stay, are not well ventilated or even if there is no ventilation system. An AC can also be used for complementing the ventilation system which always needs to be implemented first; this was recalled during the recent COVID-19 pandemic by French authorities ((Haut Conseil de la Santé Publique (HCSP, 2021), (Institut National de Recherche et de Sécurité (INRS, 2020)). Airborne fine particles are especially considered because they are harmful (they can penetrate deep into the respiratory tract and the bloodstream) and most of the commercially available ACs are designed to treat particles. The most widely used technique is mechanical filtration implemented with HEPA filters (NF EN 1822-1, 2019) but electrostatic precipitation, ionization, photocatalysis, cold plasma are also available.

Numerous studies in the literature underscore the potential of ACs in the control of the airborne particle concentrations in commercial and residential buildings. For example, in the United States, it has been shown by Carmona *et al.* (Carmona, et al., 2022) that utilizing ACs with HEPA filter (at a flowrate of 850 m³/h) positioned at the centre of the classrooms resulted in indoors ultrafine airborne particle concentrations being ten times lower than outdoors levels, whereas this ratio was only halved without AC usage. In the study of Duill *et al.* (Duill, Schulz, Jain, & van Wachen, 2023), 2 small ACs (3 to 4 units used simultaneously) and 4 large ACs (only 1 unit utilized at a time), equipped with HEPA filters, were deployed within a rectangular classroom. It was shown that the decay rate increases when the total airflow rate increases. With the 2 large ACs, the particle concentration was divided by 10 after 30 minutes, which means a decay rate of 4.6 h^{-1}; this result was obtained with a sound level lower than 40 dB(A). With the 2 small ACs the same result was obtained, albeit at higher sound level (40 dB(A) was reached at 3.1 to 3.4 h^{-1}). The decay rate was the same at the 2 different measuring points located along the length of the classroom regardless of the tested ACs. Moreover, the decay rate was higher when the clean air was released upward and horizontally by the AC (highlighting the impact of the flow pattern). In the study of Curtius *et al.* (Curtius, Grandin, & Schrod, 2021), 4 identical ACs equipped with HEPA filter (total 1026 m³/h, 5.5 vol/h) were installed within a non-ventilated classroom. It was observed that the particle concentration (0.01 to 10 µm) measured at 5 different positions decreases by 95% after 37 minutes and this decrease is similar at the 4 positions; also, there is little influence on the particle size. Furthermore, in a study by Kähler *et al.* (Kähler, Hain, & Fuchs, 2023), conducted in a meeting room, an AC equipped with an HEPA filter (with air inlet at the bottom and outlet at the top on 4 sides, inclined at 25° to the vertical axis) was placed both at the centre of the room and in a corner. The results show that the cleaning efficiency increases with airflow, the aerosol particle concentration decay rate k increases from 2.9 to 3.3 h^{-1} at 600 m³/h to 5.7 to 6.3 h^{-1} at 1500 m³/h, depending on the position of the measuring point. Furthermore, the presence of occupants does not significantly affect the cleaning efficiency. However, a slight enhancement in efficiency was observed when the room contains chairs and tables, with airflow preferably directed above the tables. Moreover, cleaning efficiency was found to be higher in square rooms compared to rectangular ones, with significantly higher efficiency near the AC in the latter case.

A lot of the available studies in this field lack comprehensive documentation, particularly regarding details such as buildings specifications, ventilation system, and AC types.

Our study focuses on the ability to mitigate the airborne particle concentrations in a mechanically ventilated meeting room with ACs equipped with HEPA filter as function of different factors, such as the number and type of AC devices, total airflow rates, airflow patterns, and AC placement(s). Through systematic experimentation and simulations, our study aims to provide valuable insights into the most effective strategies for utilizing ACs in tertiary buildings to improve indoor air quality by reducing airborne fine particle concentrations.

2 METHOD

Simulations and measurements were carried out to evaluate the efficiency of ACs in a CETIAT meeting room. The ACs selected were subjected to experimental tests to determine their intrinsic performances, which was necessary for the CFD simulations. Low-cost particle sensors were used for the measurements. Initially, these sensors were placed near each other to assess the consistency of the measured values and to calibrate them if any discrepancies were detected. Subsequently, these sensors were used in the measurement campaign to verify the overall performance of certain ACs in the meeting room and to validate the numerical simulations. The following sections describe the ACs selected, the methods used to assess intrinsic and overall performance, and the simulation model.

2.1 The studied stand-alone air cleaners (ACs)

Six ACs equipped with HEPA filter (as illustrated in Figure 1) were selected for the study. This selection includes four mobile units: three floor types (designated as C, D, and F) and one table type (labeled as B). Additionally, two fix units were included: ceiling-type models (identified as A and E). This selection is made to ensure representation of commercially available products on the French market and to include a variety of flow patterns, characterized by different air inlet and outlet positions synthetized in Table 1. The main characteristics of the ACs are provided in Table 2.

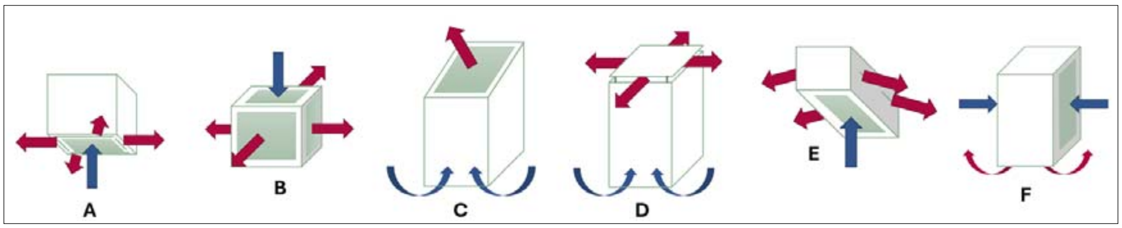


Figure 1: The six stand-alone air cleaners (ACs) studied

Table 1: Position of inlet and outlet of the 6 studied AC models

Model	A	B	C	D	E	F
Inlet	Bottom face	Top face	Floor level	Floor level	Bottom face	Two opposite side faces
Outlet	Horizontal on all four sides	Horizontal on all four side faces	Upward inclined at 45°	Horizontal at the top in all directions	Horizontal, on two long vertical sides	Floor level

Table 2: Main characteristics of the six stand-alone air cleaners (AC) studied

Unit	A	B	C	D	E	F
Type	Ceiling	Floor	Floor	Floor	Ceiling	Floor
Dimensions (cm)*	59/60/36	42/43/40	45/37/96	69/67/113	59/89/30	34/34/72
Main filter**	H14	H14	H13	H14	H14	H14
Air flow rate (m^3/h)***	200 max	1000 max	200 to 900	1200 max	300 max	37 to 433

** Length/Width/Height; ** As per EN 1822-1 (2019); *** Manufacturer's data*

2.2 Measurement of the intrinsic performances of the stand-alone air cleaners (ACs)

The intrinsic performances of the ACs have been measured according to the French standard (NF B 44-200, 2016). This standard provides a method for measuring specified product performances especially airflow, particulate matter removal efficiency, electric operating power, and sound power level. It references EN ISO 5801 (2017) for airflow measurement and EN ISO 3743-1 (2010) for sound power level measurement. For assessing particulate matter removal efficiency, the AC under test is installed within a test duct, its inlet placed upstream, and its outlet placed downstream utilizing a specially designed separator plate. An auxiliary fan is used to equalize pressure between the AC's upstream and downstream sections, reproducing real operating conditions. Particles of DEHS (Di-Ethyl-Hexyl-Sebacat) are continuously injected upstream, and concentration measurements are taken upstream and downstream of the AC.

2.3 Meeting room

For this study, a meeting room located at CETIAT was chosen. The room is rectangular, measuring 7.9 m x 4.7 m, with a total volume of 80 m³, and is mechanically ventilated at approximatively 1.5 vol/h. It features two exhaust valves (outlets) positioned on the ceiling and 3 fresh air inlets located above the windows (refer to Figure 2 a)). The room is furnished with tables, chairs, cupboards, and fan coil units (VC). For simplification of the geometry, the chairs are not included in the room model.

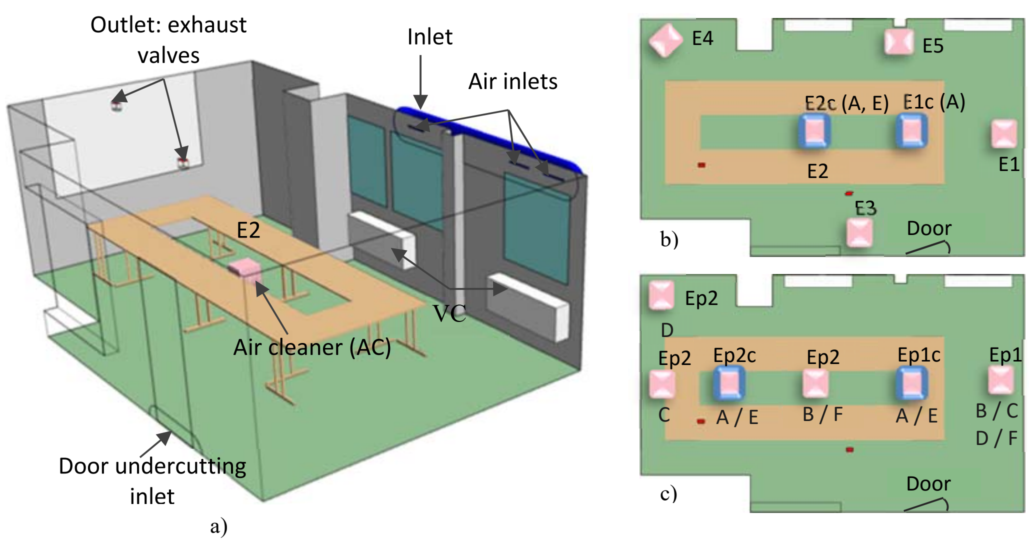


Figure 2: Views of the meeting room: geometry and boundary conditions (a)); AC simulation positions with one unit (b)) and with two units (c))

2.4 Numerical simulation method

A stationary three-dimensional computational fluid dynamics (CFD) modeling of the AC within the meeting room was conducted to assess cleaning efficiency relative to various factors including airflow rate, AC positioning, device quantity and type, and air flow pattern. A commercial CFD software was employed to conduct the simulations. The computational domain reproduces the full-scale meeting room with the AC installed (refer to Figure 2 a)). The mesh features a refined mesh near the air inlets and outlets including a boundary-layer grid near the wall surfaces and a coarser mesh elsewhere in the computational domain. The final volume mesh grid comprises approximatively 10.2 million of polyhedral elements. Flow pattern simulations employed steady Navier-Stokes equations with a two-layer k-ε turbulence model, integrating all y+ wall treatment. A Eulerian species model was utilized to simulate aerosol particle dispersion, with CO_2 serving as the tracer gas. This approach is applicable for modeling particles with diameters less than 5 µm, which remain suspended in the air for many hours ((Castellini, Faulkner, Zuo, Lorenzetti, & Sohn, 2022); (Noakes, Fletcher, Beggs, Sleigh, & Kerr, 2004)).

For each AC, simulations were conducted for nearly five different positions and two airflow rates corresponding to 1 or 2.5 air changes per hour (ACH), as well as 5 ACH of the room volume. One type of AC at a time was positioned at locations E1 to E5 on the floor, (ACs B, C, D and F) or table (AC B), and at the positions E1c and E2c on the ceiling (AC A) as shown in Figure 2 b) and 2 c). AC E was positioned in the center of the ceiling, in position E1c, the air outlet flows in the direction of the width of the room and in position E2c in the direction of the length of the room. Additionally, configurations with two ACs were simulated, with their positions labeled as "Ep" on Figure 2c.
The inlet and outlet air boundary conditions were set as “Velocity Inlet” while the door undercutting inlet was set as a reference pressure condition. The inlet and outlet of the ACs were set as velocity inlets corresponding to airflow rates of 1 or 2.5 ACH and 5 ACH. The particle concentration at the AC outlet equaled that at the inlet, which was reduced by the experimentally obtained AC efficiency. For each scenario, an initial calculation of steady-state airflow fields was conducted. Subsequently, transient simulations were initiated to model particle concentration in the room as the ACs operated for 60 minutes. These simulations employed a 2-minute time step, allowing observation of concentration level changes over time.

2.5 Experimental method

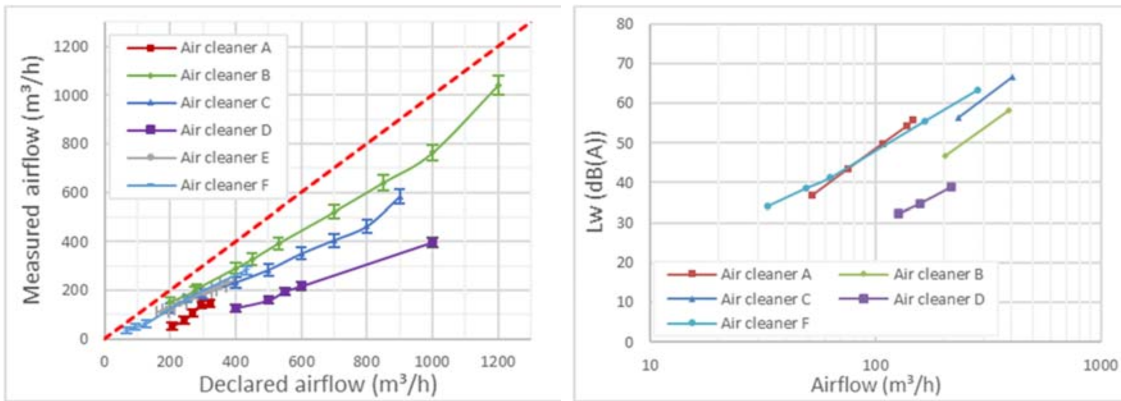
The airborne particle concentrations within the meeting room were measured with low-cost particle sensors. These sensors continuously count particles as function of their size, ranging from 0.3 µm up to more than 5 µm. Particles are classified in 5 channels: 0.3-0.5 µm, 0.5-1.0 µm, 1.0-2.5 µm, 2.5-5.0 µm and > 5.0 µm. Nine sensors were used indoors: one positioned near one of the 2 air outlets and eight evenly spaced over the tables at a height of 1.2 m. The particle concentration was recorded every 10 seconds and expressed in number per cubic meter of air.
Before measurements within the meeting room, the nine particle sensors were compared to assess whether the measurements are consistent when placed in the same location. This experience has been done in an office room at CETIAT, where an AC was used to vary particle concentration and to ensure that the sensors are compared over a wide airborne particle concentration. While the sensors give very different values (with a factor of around 2 between the lowest and the highest values), they record the same trend when the particle concentration decreases (AC on) or increases (AC off). As the sensors are supposed to provide the same data, it was decided to adjust the values of the other 8 sensors to match those of the PS9 sensor. Linear regression analyses were performed between each of the 8 other sensors and the PS9 sensor ($R^2 > 0.99$) to determine the correction factor. This correction methodology was subsequently applied to measurements done within the meeting room (refer to paragraph 3.3).

3 RESULTS AND DISCUSSION

The intrinsic performances of the stand-alone air cleaners (ACs), simulations and measurements results are presented in this paragraph. For the simulations and measurements, the results are principally expressed as the ratio between the particle concentration after 16 minutes of operation (C16) and the initial concentration (C0). By focusing the analysis on this 16-minute performance metric, the results shed light on a key aspect of the AC' real-world effectiveness in improving indoor environments where people are present.

3.1 Intrinsic performances of the ACs

Figure 3 a) and b) display the measured airflow and sound power level, respectively. The results show that the targeted airflows for this study, ranging from 80 to 400 m³/h, were successfully achieved. However, it's noteworthy that the measured airflows for all ACs were observed to be below the manufacturer's declared data (refer to Figure 3 a)). Acoustic pressure level measurements (Figure 3 b)) reveal that most of the ACs generate more than 50 dB(A) when operating above 200 m³/h. While this has no impact on particulate matter removal, it raises the question of noise acceptability for users. Such levels of noise can become annoying in environments as a meeting room, offices, and especially bedrooms.



a) b)

Figure 3: Intrinsic performance measurements results. Air flow (a)), sound power level (Lw) (b))

The particulate matter removal efficiency obtained exceeds 99% for all ACs, with only one exception where it was around 95%. These results align with expectations for HEPA filters. Upon examination of the AC with the lower efficiency, a leak was revealed between the filter and the mounting frame. However, this isolated incident does not undermine the overall effectiveness of HEPA filters.

3.2 Simulations results

Figures 4 through 6 present the simulation results. Figures at left show the results for the floor and table ACs, while Figures at right display the results for the ceiling mounted ACs.
Figure 4 shows the particle concentration C16/C0 in the meeting room for the different ACs positioned at location E2, as a function of the airflow rate expressed in air changes per hour (vol/h). The results show that increasing the airflow rate led to a significant reduction in particle concentration in the room after 16 minutes of AC operation. For the floor ACs, increasing the airflow rate from 2.5 to 5 vol/h resulted in a 31% decrease in the C16/C0 ratio (see Figure 5a)). For the ceiling mounted ACs, increasing the airflow rate from 1 to 2.5 vol/h led to a 25% decrease in the C16/C0 ratio (see Figure 5a)).

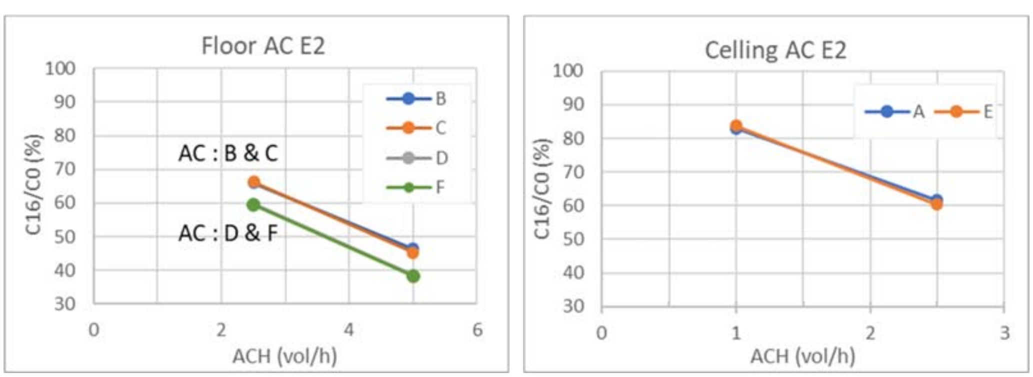


Figure 4: Impact of the ACH on the particle concentration after 16 minutes of AC operation

In summary, the results show that higher airflow rates through the AC, whether floor or ceiling mounted, led to more effective reduction of particle concentrations in the meeting room over a 16-minutes period. A slightly superior performance was observed when increasing airflow for floor AC. However, it is important to note that increasing the AC airflow rate does not necessarily translate to a proportionate improvement in air cleaning efficiency, underscoring the importance of judiciously selecting the type of AC and airflow rate setting based on the specific needs of the indoor environment.
Figure 5 illustrates the particle concentrations C16/C0 ratio, in the meeting room with single and two units of each type of AC. The results are shown for the floor ACs operating at an airflow rate of 5 vol/h and the ceiling mounted ACs operating at 2.5 vol/h. The results show that increasing the number of floor AC from 1 to 2 had varying effects on the performance of different models. For some ACs, like B and C, the particle removal efficiency was improved with the additional AC. For others, like D and F, a performance decrease is noted when going from 1 to 2 ACs. Increasing the number of ceiling mounted ACs from 1 to 2 units did not have a significant impact on the particle removal performance for both ACs models A and E. In summary, the data suggests that the AC type and the number of units deployed can impact the overall particle concentration reduction achieved in the space. The optimal configuration appears to depend on the specific AC models being used.

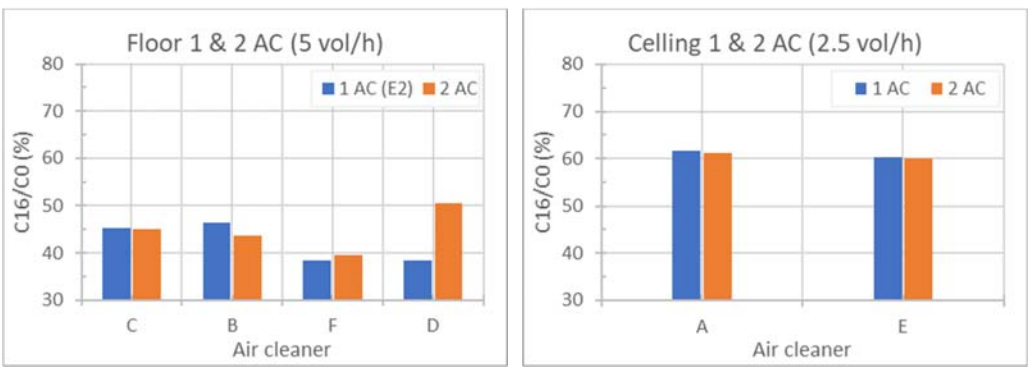


Figure 5: Impact of the AC number on the particle concentration after 16 minutes of AC operation

Figure 6 displays the C16/C0 ratio for the ACs positioned in locations E1 to E5 within the meeting room. The results show that the location of the floor ACs within the room had a significant impact on their particle removal performance. Location E2 seemed to be the most favourable position, while location E4 generally resulted in the higher C16/C0 ratios for the different AC models.

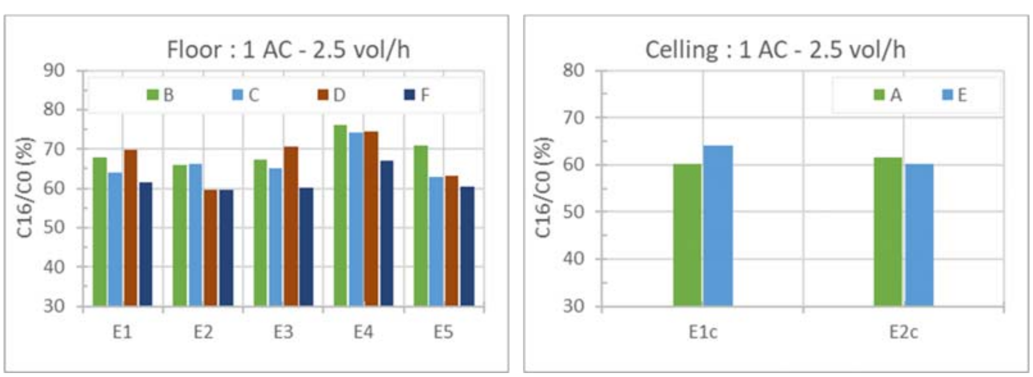


Figure 6: Impact of the AC position on the particle concentration after 16 minutes of AC operation

For the AC C, the better performance was achieved in location E5, with a C16/C0 ratio of 63%. For the ceiling AC A, the location E1c seems to be better, with C16/C0 slightly lower than in location E2c. For the AC E, the location E2c is better than the location Ec1. The results highlight that, factors such as airflow patterns, room geometry, and potential obstructions in the space can influence the effectiveness of in-room ACs. Careful consideration of the placement of these devices is important to optimize their performance in reducing airborne particle levels.

3.3 Measurements results

The measurements were conducted for 9 configurations amongst the 66 studied through numerical simulations. An example of the results of such measurements is presented in Figure 7, with measurements taken on February 28 and 29, 2024. For this example, the AC D was positioned in location E1. Its airflow rate was set at 200 m³/h (equivalent to 2.5 vol/h). The AC was alternatively turned on and off, and it results in short decreases and increases of the particle concentration over time.

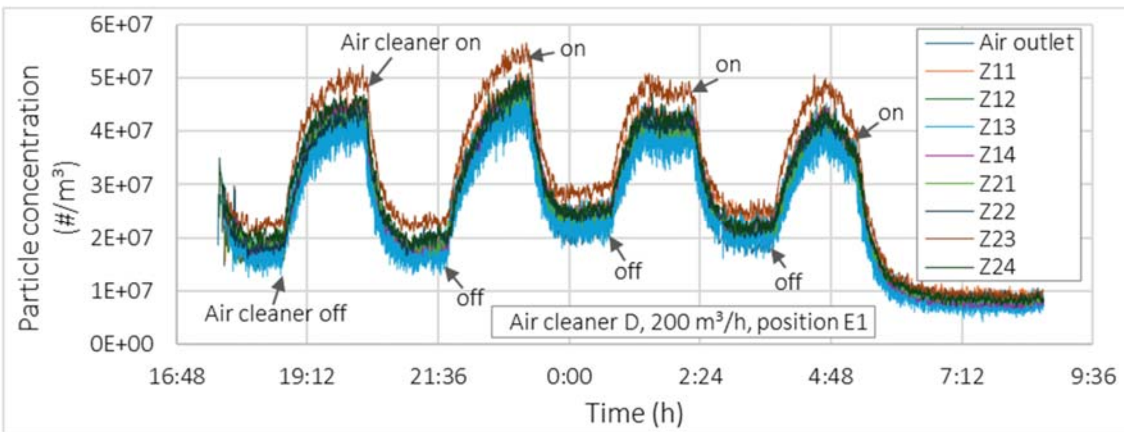


Figure 7: Particle concentration (0.3 – 0.5 µm) in the meeting room with the AC D at position E1

Figure 8 presents the particle concentration after 16 minutes (C16) compared to the initial concentration (C0) in box plot form, including both experimental (Meas) and simulation (Simul) results. A lower C16/C0 ratio means a higher decrease in particle concentrations. The box plots are built based on data obtained from 8 sensors uniformly spaced over the tables at a height of 1.2 m for the measurements. For the simulations, the box plots are derived from the volume average of 8 breath zones extending up to the tables.

The experimental results show that increasing the airflow rate of the AC leads to a higher decrease of the overall particle concentration. Specifically, the mean C16/C0 ratio ranges between 63 and 72% at 2.5 vol/h, between 58 and 60% at 3.5 vol/h, and between 41 and 55% at 5 vol/h, depending on the AC type and its location within the room. Similar trends are obtained by simulations. Specifically, the concentration (C16/C0) ranges between 63% and 73% at 2.5 vol/h, decreases to 53% at 3.5 vol/h, and ranges between 44% and 55% at 5 vol/h (refer to the preceding paragraph and Figure 8).

The height of the box plot indicates the homogeneity of the concentrations between the 8 points: a smaller box plot suggests that the impact of the AC is homogenous between the points, while a higher box plot means less uniformity, with some areas being better cleaned than others. The results, shown in Figure 8, highlight that the decrease in particle concentration varies for the different areas of the room, indicating that effectiveness of the AC is influenced by airflow patterns.

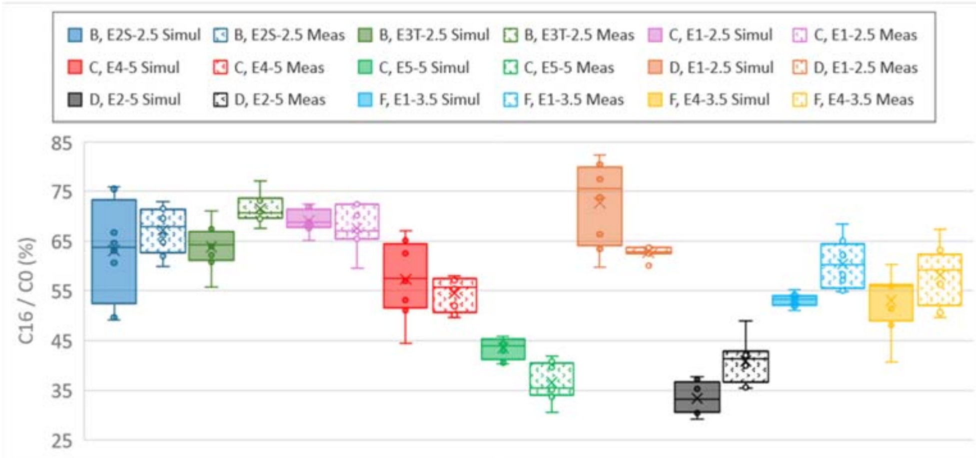


Figure 8: Normalized particle concentration (C16/C0) after 16 minutes of ACs operation

The simulations (CFD) and experimental data of the particle concentrations after 16 minutes of the ACs use show close values but some differences are observed and may be explained for different reasons:

- Differences in flow patterns. The CFD simulations assume constant inlet airflow rates, with 88% of the total extracted flow coming from the outside via the "Inlet" and 12% coming from the corridor. However, the actual inlet airflow rates from outdoors and corridor are not measured, and this assumption may not accurately reflect the actual inlet airflow rates.
- Differences in meeting room layout. The CFD simulation does not consider the chairs in the meeting room, which can impact airflow and particle dispersion.
- Differences in measurement methods. The particle concentrations are measured at single points whereas the CFD simulation considers particle concentration integrated values over a rectangular zone leading to potential discrepancies.
- Assumptions regarding outdoor and corridor particle concentrations: CFD simulation assume constant outdoors and corridor particle concentrations, which may fluctuate over time, during the measurements campaign.

4 CONCLUSIONS

Our parametric study has allowed to a better understanding of the ways to implement stand-alone air cleaners (ACs) equipped with HEPA filter in a meeting room. The simulation results show that when the total airflow rate involved by 1 or 2 stand-alone air cleaners (ACs) increases, the cleaning efficiency increases, and the airborne particle concentration obtained after 16 minutes of ACs use decreases.
When the AC is positioned at the centre of the room, higher performances levels are obtained. Inversely, when the AC is in a corner behind a wall, the performances are lower compared to other positions of ACs in the room. The differences in particle concentrations across the room when an AC is used are weak at 5 vol/h but become larger at 2.5 vol/h; airborne particle concentrations within the room are more homogeneous with the ceiling-type ACs.

Out of the 66 configurations studied through simulation, nine were assessed using experimental particle concentration measurements with low-cost particle sensors (between 0.3 and 5 µm). The overall air cleaning efficiency tendencies observed experimentally are in line with those

obtained by simulation. However, comparing air cleaning efficiencies across the room is more difficult due to different hypotheses in simulation and measurements.
Most of the ACs have sound power levels exceeding 50 dB(A) above 200 m^3/h, which can cause noise nuisance for occupants; thus, this parameter must be considered.
This study is limited to a single rectangular meeting room, and additional studies in various types of indoor spaces are necessary to establish guidelines for the implementation of stand-alone air cleaners in tertiary buildings. Future research directions include investigating the effectiveness of stand-alone ACs in mitigating the airborne particle concentration within a non-ventilated larger, square-shaped meeting room.

5 ACKNOWLEDGEMENTS

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