Ventilation and air cleaning in the context of infection risk – results from two large Dutch research projects

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SUMMARY
Ventilation and air cleaning are two important means of supporting indoor air quality in the context of the risk of exposure to pathogens. This paper presents two results, from Dutch research projects, related to expressing ventilation effectiveness and portable air cleaner performance. A new test facility was used in this research. The results show that in-room performance indicators like the source-specified surface-averaged concentration add to the understanding of ventilation performance in the context of contaminant exposure. For portable air cleaners, the standardized clean air delivery rate (CADR) assessment procedure is relatively robust, but local variations in a large room are better captured by the so-called practical CADR assessment procedure.

KEYWORDS
Exposure; Ventilation effectiveness; Air cleaning; CFD; Measurements.

1 INTRODUCTION
The Covid-19 pandemic has been a reminder of what the impact can be when we are in contact with airborne pathogens to which we don't yet have resistance. This pandemic was able to change a persistent dogma of the last ~100 years that airborne infection was not an important means of disease transmission (Jimenez et al., 2022). As a result, more attention is being paid to the quality of indoor air.

Although source control is the best strategy to improve the indoor air quality, it is often not feasible. Therefore, since Covid-19, more attention is paid to ventilation and air cleaning (Morawska et al. 2020). Also in the Netherlands, several research projects have been initiated to improve our understanding of the effectiveness of ventilation and (portable) air cleaning in the context of pathogen removal (P3Venti; www.p3venti.nl; CLAIRE; claireproject.nl). In these projects, general research questions to be answered relate to how to assess the performance of a ventilation design and how portable air cleaners perform in realistic situations. This paper presents two results of novel work done to support the answers to these general research questions, one concerning the ventilation effectiveness and one related to the performance of a portable air cleaner.

2 METHODS
As part of answering the research questions, a large test facility was designed and built at the Eindhoven University of Technology (see Figure 1, left). This large room

is assumed to be representative of a classroom or living room in a long-term care facility. The room is used for airflow research, to provide validation data for CFD simulations, and to test the performance of portable air cleaners.

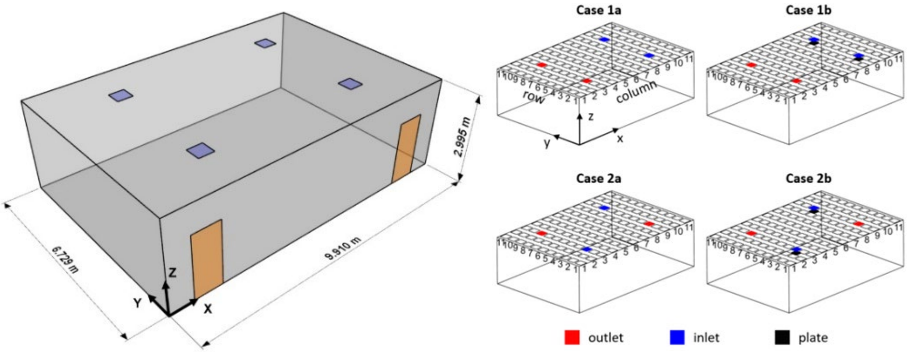

Figure 1. Schematic drawing of the test facility, including its dimensions (left). Investigated cases with different supply and exhaust configurations (right).

The test facility is equipped with an HVAC system capable of supplying conditioned HEPA-filtered air up to an air change rate of 6 h^{-1}. The room is airtight, resulting in an infiltration rate of 0.01 h^{-1}.

2.1 Ventilation effectiveness

As part of the design process, the test facility was analyzed using Computational Fluid Dynamics (CFD) to study the flow field. This analysis has been published elsewhere (Kang et al., 2024). Figure 1 (right) shows the cases studied as part of that analysis. It is an isothermal case with two supply and two exhaust grilles in the ceiling. The supply was designed as a perforated grille. For cases 1b and 2b, a plate was fixed 100 mm below the grille to force the air horizontally into the room. An air exchange rate of 3 h^{-1} was assumed for each case.

The CFD simulations in this study use the same computational domain, grid, boundary conditions, and solver settings as in the study by Kang et al. (2024). In addition, a total of 121 source locations at the breathing height (i.e. 1.2 m height), instead of the two source locations studied by Kang et al. (2024), are considered here to further investigate and visualize the ventilation effectiveness for different source locations. The developed procedure assumes a constant contaminant source that is released consecutively in a horizontal and regular grid (11×11) across the room. No momentum is assumed for the release of the contaminant. This assumption allows the flow field in the CFD simulations to be fixed and only the contaminant distribution in the room to be calculated. This is done for each source location on the grid. Next, the results are presented as an average pollutant concentration for a selected plane in the space. Since the interest is in human pathogen emissions, the grid of sources is assumed at the level of the mouth (0.1 m diameter sphere with CO_2 emission rate of 0.001 $kg/m^3/s$ at 1.2m height). Similarly, assuming that breathing takes place at a similar height, the interest is in the concentration field at breathing height. Therefore, the average concentration in the room as a function of the source location is calculated for this height.

2.2 Portable air cleaner performance

The performance of portable air cleaners (PACs) was also tested in the large test facility. A comparison was made between analyzing the performance of a PAC according to the ANSI/AHAM standard (ANSI/AHAM, 2020), which should be performed in a ~28 m^3 room, and the performance in a realistically sized room (large test facility ~200 m^3). The performance is expressed in Clean Air Delivery Rate (CADR [m^3/h]). The resulting CADR is referred to as the theoretical CADR ($CADR_{th}$). An alternative approach following another standard (DIN/TS 67506; Deutsches Institut für Normung, 2022) was investigated as well. The resulting CADR from this analysis is called the practical CADR ($CADR_{pr}$).

The DIN/TS 67506 method is almost identical to ANSI/AHAM. Both compare a situation with only natural decay of aerosols and a situation with the PAC on. However, for the DIN/TS 67506 method the fans in the room are switched off at the start of the decay measurements. So air movement in the room then is limited for natural decay measurements, or only the result from the active PAC. In the ANSI/AHAM standard the fans are kept running during both decay measurements. In this paper the effect of the room size and difference in outcome for the two standards are presented for a specific PAC. Figure 2 shows a schematic of the type of PAC studied and the set-up in the ANSI/AHAM test room and the large test facility (Xia et al. 2024). All measurements were repeated three times.

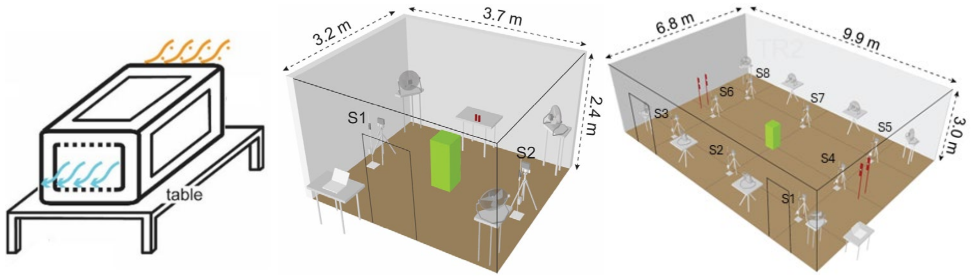

Figure 2. Schematic of the investigated PAC (left). Lay-out of the measurement set-up in the 28 m^3 test room (middle) and large test facility (right). S1-2/S1-8 represent the positions of the particle counters. Fans are visualized as well. The green box represents the position of the PAC.

The results are presented as $CADR_{th}$ and $CADR_{pr,}$ for the particle sizes monitored. In the analysis, the sensitivity towards the time interval used for calculating the decay rate was also investigated. Comparisons are made in terms of CADR for the relative $CADR_{th}$ difference between the ANSI/AHAM standard room size and the large room size of the test facility (D_{th}), the relative difference between the $CADR_{th}$ from the ANSI/AHAM standard room size and $CADR_{pr}$ from the large room ($D_{pr\text{-}th,\ TR1}$) and the relative difference between $CADR_{th}$ and $CADR_{pr}$, both for the large room ($D_{pr\text{-}th,\ TR2}$). Such comparisons have not been presented earlier.

3 RESULTS AND DISCUSSION

3.1 Ventilation effectiveness

Figure 3 shows results of the airflow in the room for the four cases presented in Figure 1. The velocity path lines clearly show the effect of the plates on the flow field in the room (case 1b and 2b). Figure 4 shows the surface-averaged mass fraction of the pollutant at a height of 1.2 m for a grid of 11×11 uniformly distributed source positions, for the four cases studied. Note that in this case the pollutant (CO_2) is a gaseous pollutant. Assuming, for example, the drift-flux model, it is possible to account for aerosols and calculate their distribution similarly.

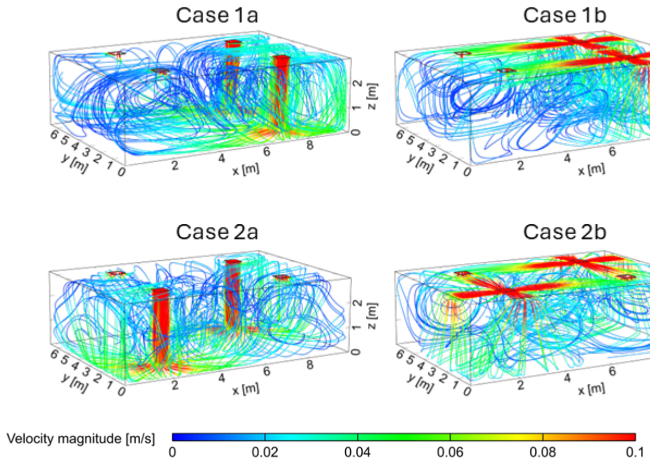

Figure 3. Velocity path lines for the different cases.

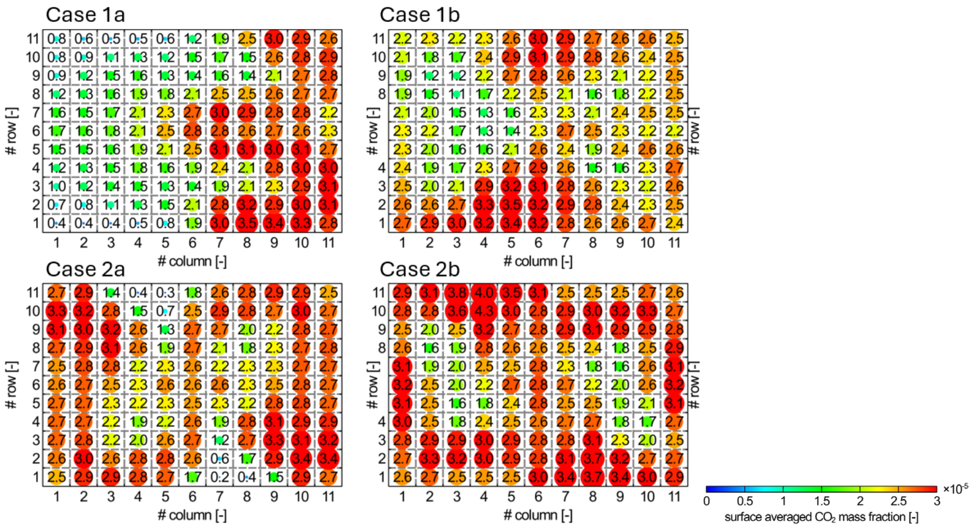

Figure 4. Surface averaged CO_2 mass-fraction at a horizontal plane at 1.2 m height. Sources are positioned at a 11×11 uniform grid (each cell represents one case).

The results show that the design of the supply and the position of the supply and exhaust influence the removal of contaminants in a room. The developed procedure differs from the analysis of the air change efficiency (REHVA, 2004) in that individual source locations are examined. Although the absolute results are shown in Figure 4, the procedure has a clear resemblance to the assessment of the contaminant removal effectiveness. In this case, the capabilities of CFD are used to calculate the distribution of the contamination in the room. Only average results are shown in the example. Nevertheless, the available information can be used to identify the distribution of the contamination. For example, the standard deviation, assuming a normal distribution, or a box plot can provide an indication of the concentration variation throughout the plane. The visualization then has to be updated. Alternatively, areas can be selected to focus the results, rather than an area average for the entire room. This would allow a better assessment of the risk of exposure within a room when the location of the source is not known.

3.2 Portable air cleaner performance

Table 1 shows the $CADR_{th}$ for the two rooms and $CADR_{pr}$ for the large room. The results are presented as a function of the number of data points (time interval) that have been used to analyse the decay, and the particle size. A larger number of data points improves the evaluation of the CADR.

Table 1. $CADR_{th}$, $CADR_{pr}$, and the relative difference for the investigated air cleaner across various particle sizes (0.25, 0.25-0.5, 0.5-3, 3-10 µm), data points (related to time interval) and rooms (TR1: small room; TR2: large room).

Parameter	Data points	PM0.25	PM0.25-0.5	PM0.5-0.3	PM3-10
$CADR_{th,TR1}$ (m^3/h)	12	334	342	351	368
	9	302	309	321	434
$CADR_{th,TR2}$ (m^3/h)	12	319	325	333	433
	19	329	333	339	422
	12	364	371	388	439
$CADR_{pr,TR2}$ (m^3/h)	30	355	360	374	447
	50	366	370	382	457
D_{th} (%)	12 TR1, 19 TR2	-2	-3	-3	15
$D_{pr-th, TR1}$ (%)	12 TR1, 50 TR2	10	8	9	24
$D_{pr-th, TR2}$ (%)	19 TR2, 50 TR2	11	11	13	8

From Table 1 it can be concluded that for larger particles (PM3-10) the CADR for the large room is in the order of 20% larger than that for the smaller room. This is similar when compared to the smaller particle sizes for the large room. It is assumed that deposition contributes to the CADR obtained. It is noteworthy that the difference $D_{pr-th,TR2}$ is similar for all particle sizes. This indicates that, due to the way the CADR is determined, the deposition is not really affected by the additional air movement caused by the fans, as applied for determining $CADR_{th}$. Not shown in Table 1, but identified from the individual results of the particle counters (S1-S8; Figure 2), the situation without the fans operating ($CADR_{pr}$) results in more variation between the particle counters, up to an order of 100%, especially for larger particles (PM3-10). So, while the averages at room level between a theoretical assessment according to ANSI/AHAM and a practical assessment according to DIN don't show much differences, locally it can be expected that $CADR_{pr}$ gives more realistic performance levels for the air cleaner.

4 CONCLUSION

The paper presents two results from ongoing research as part of two large Dutch research projects focussed at the mitigation of pathogen exposure through ventilation and air cleaning.

For ventilation, the proposed methodology to investigate the contaminant distribution in a room extends the option to assess the performance of a ventilation design. It provides an insightful assessment of the effectiveness with which contaminant with an unknown source location can be removed from a room. The rich CFD data can be used to extend the assessment, e.g., to fine-tune the analysis to zones in the room.

For air cleaners, different evaluation methods (room size/standards) were tested to assess their impact on the performance of a PAC. For the PAC studied, the room size is most important, especially for the larger particle sizes (PM3-10). Evaluation of the CADR with fans on (theoretical approach) or fans off (practical approach) shows relatively small differences. Results from the practical approach, however, do show local variations of the CADR throughout the investigated room.

Research on extensions of the analysis of the ventilation performance continues. Among other things, the effect of a momentum source in the release of a contaminant is being investigated. Air cleaner performance tests are extended by including the effect of the position of the air cleaner in the room and combining it with ventilation.

5 ACKNOWLEDGEMENT

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