Tracing of Sars-CoV-2 aerosols with tracer gases in an occupied classroom with mobile air cleaners

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ABSTRACT

The placement of mobile air cleaners (MACs) in classrooms was widely discussed between parents, teachers, and authorities in Germany during the peak of Corona infections in 2020 and 2021. Measurements of mobile air cleaner efficiencies in larger laboratory rooms indicated that there are substantial efficiency differences between test results in a real room compared to results measured in a standardized 28m³ well-mixed clean test room according to a standard. The test method described here overcomes the multiple problems and uncertainties of aerosol particle decay tests. However, this method can only be applied to mobile air cleaners having a particle filter and an active carbon filter.
Sars-CoV-2 viruses are always attached to aerosol particles. 99% of exhaled aerosol particles are smaller than 2 microns and therefore completely airborne. This is the reason why a tracer gas can be used to mimic the flow pattern of aerosol particles where potential viruses could be attached to. Tracer gases in general are not affected by particle filters, they go just through. While aerosol particles accumulate in the HEPA filter of the MAC Perfluorocarbon tracer (PFT) are at the same time adsorbed by a downstream or upstream active carbon filter. The proportionality between particles removed by the particle filter and PFT removed by the active carbon filter is used to study the aerosol particle removal efficiency and spreading in a classroom. The Perfluorocarbon tracer PMCH was used to measure the effective clean air delivery rate in the occupied zone of a classroom. Constant injection of diluted PDCB was used to mimic the spreading of aerosol particles by an infected pupil sitting at a desk.
The paper describes an efficiency test for mobile air cleaners in an occupied classroom with 22 pupils and a teacher present. Tracer gas sampling was done by the pupils themselves at every desk in the breathing zone, at the inlet of each air cleaner and at the outlet of each air cleaner using 60cc syringes. The syringes were later analysed by an Autotrac 101 tracer gas monitor, a gas chromatograph with electron capture detector. With this strategy a complete picture of aerosol resp. tracer gas migration and decay could be established.
SF_6 as a third tracer gas was used to account and correct for removal of particles by infiltration. Local PMCH decay data provided local removal efficiencies at all desk locations. By evaluating PDCB migration data, local exposure values could be calculated for every desk and pupil in the classroom.
By comparing the PMCH concentrations in the occupied zone with the PMCH inlet concentration of the mobile air cleaners it was possible to quantify short circuiting around the MACs, i.e., the flow of cleaned air at the MAC outlet which circulates directly to the MAC inlet without affecting the occupied zone.

KEYWORDS

Tracer gas test, Perfluorocarbon tracer, PDCB, PMCH, SF6, Sars-CoV-2, corona, virus exposition

1 INTRODUCTION

Roughly 90% of German schools are naturally ventilated. A discussion about the need of mechanical ventilation systems in schools started again with Corona infections when classes and complete schools were closed for weeks. The German Environmental Agency UBA recommended plug ventilation every 20 minutes for a duration 3-5 minutes and in rooms where plug ventilation is not effective enough mobile air cleaners (MACs) were proposed to support natural ventilation means.

Due to pressure from parents and teachers many school authorities were forced to order MACs and the question arose what kind of specification is needed and how effective should MACs are. Measurements indicated that the Clean Air Delivery Rate, which should be specified by the manufacturer based on a proven standard, is not reached in real classrooms.

For clarification: The Clean Air Delivery Rate, CADR, is the airflow through a MAC which is completely cleaned from particulate matter (dust, cigarette smoke, and pollen). A common test standard is *ASTM/ANSI AC-0001*, revised in 2020. Inefficiencies in the particle filter performance or leakage around the filter frame leads to a CADR which is lower than the physical airflow throw the MAC. The CADR is measured in a 28m³ test chamber where complete mixing is maintained throughout the test. A standardized amount of a particle species is released using an aerosol generator and mixed with the test chamber air. In a first step the natural decay rate is monitored without the MAC in operation. Then a second identical test is performed with the MAC in operation. Using these results, the CADR is defined as the difference between both decay rates multiplied by the test chamber volume. The CADR characterizes the cleaning capacity of a device, it does not characterize its performance in a real room.

Tests with MACs in real rooms indicate up to 25% lower particle removal performance as expected from the specified CADR, *Kähler et all, 2020*. One reason is short circuiting of already cleaned air from the MAC outlet directly to the inlet without flushing or mixing with the room air. The higher the flowrate the higher is the risk of short circuiting. Other reasons for poor performance are placement of MAC behind furniture or in locations which encumber good ventilation of the occupied zone.

An average German classroom has 200m³ volume and 3m ceiling height. The average occupation is 25 pupils. They create buoyancy flows which are fed from the floor area and move upwards in the order of 2.000m³/h (approx. 80m³/(h person)). Looking at flow rates for MACs in classrooms recommendations range between 4 and 6 air changes per hour. For the average German classroom of 200m³ this is 800m³/h to 1200m³/h. The fan(s) of one or several MACs support also mixing of the room air. Regarding particles however, an operating MAC constitutes a sharp particle concentration gradient at its location, high concentration at the inlet and almost no particle concentration at the outlet. Therefore, regarding particles, a classroom deviates from a well-mixed zone.

Sars-Cov-2-viruses are bound to aerosol particulates. Exhaled aerosols of >5µm show at normal room air velocities a trend to sediment to the ground, stay there and get inactive after a certain time. However, *Hartmann et all, 2020* had shown that over 99% of aerosols people exhale are attached to particulates smaller than 5µm. These small particles are completely airborne. Their flow pattern is identical to the flow pattern of the room air. This behaviour makes it possible to simulate the spreading of virus-laden aerosols using tracer gases.

Aerosol tracing and removal measurements in real rooms using aerosol generators and particle counters inhibit many uncertainties which are difficult to quantify:

- in real rooms and especially in classrooms there is dust deposited on surfaces. Forced airflows of MACs disperse the dust into the air
- The movement of persons in the room generates additional particles
- The opening of a window or door can reduce or increase the particle concentration in the room of concern depending on the particle concentration of the outside air or of adjacent rooms

- The particle counter is not able to differentiate between generated aerosol particles to mimic viruses and particles, set free from the movement of people or infiltrating from outside
- The number of particle counters for a test is usually limited to 1-3 units. Therefore, it is difficult to monitor at multiple locations at the same time to obtain a complete picture of the situation.

The proper selection of tracer gases and analyses techniques help to avoid many of these problems. A favorable way is the use of a gas chromatograph with electron capture detector (GC-ECD) with the following advantages:

- it detects concentrations from the ppb down to the low ppt range. Therefore, very small amounts of a tracer (some cc) are required and can be released via 60cc plastic syringes for decay tests or 1 litre lecture bottles for constant injection tests.
- For analysis just 10cc are needed which enables again the use of 60cc syringes for sampling. One can take samples at many locations at the same time, while the analysis is done later in the lab. One does not even need an analyser on site for a test.
- Due to the low room concentrations the tracer gases are allowed in occupied rooms according to *VDI 4300-7*.

2 TEST OBJECT

The UniqAir PRO MAC is shown in Figure 1. The inlet consists of 4 slits at the top, the clean air outlet is to all 4 sides close to the bottom. The air is sucked through a G4 pocket filter to eliminate larger particles before they can enter a cylindrical H13 particle filter. A 12mm thick layer of active carbon on the inner side of the cylindrical cartridge eliminates air impurities like volatile organic compounds (VOC) and nitrous oxids (NO_x). An axial fan is located beneath the filter unit. A turning knob can be used to adjust the fan speed from zero to 330m³/h.

Figure 1 Foto of mobile air cleaner UniqAir PRO (left); G4 pre-filter and view on cylindrical H13 filter flange (middle); cylindrical H13 filter with inner layer of active carbon (right)

SF_6 Tracer Gase to account for infiltration

Sulphur hexafluoride, SF_6, is an artificial gas and an almost perfect tracer. The molecule is very stable. Adsorption to walls or even active carbon filters is not measurable. For this test SF_6 was selected to measure the infiltration rate during the time of test, because infiltration can also transfer particles which should not be attributed to the performance of the MACs.

Perfluorocarbon tracer gases to monitor virus-laden particles

Perfluorocarbon tracers (PFT) have a cyclic molecule structure with a chemical formula of C_xF_y of carbon and fluorine atoms. They are artificial gases with almost no background. Electron Capture gas chromatography makes it possible to analyse PFT and SF_6 down to the low ppt-range. PFT show a good adsorption behaviour on active carbon. This is the reason why they are heavily used in military applications to measure the tightness of NBC filters[1] in shelters and vehicles.

To measure tracer gas rather than aerosol particle concentrations one makes use of the analogy that PFT are adsorbed in the active carbon filter in the same way as particles are trapped in the particle filter of the UniqAir PRO. To validate the adsorption behaviour prior to this test one UniqAir PRO device was exposed to different PFT at varying flow rates. The inlet and outlet PFT concentrations were monitored, and the removal efficiencies determined.

The two selected PFT were PDCB (C_6F_{12} - Perfluorodimethylcyclobutane) and PMCH (C_7F_{14} - Perfluoromethylcyclohexane). For the flow rates applied in the classroom test the PFT filter efficiency for PDCB was >99% and for PMCH >98%.

3 SCOPE OF TEST

The Finnish MAC manufacturer UniqAir with a subsidiary in Germany asked for a test to qualify the performance of UniqAir mobile Air Cleaner PRO in a real classroom under full occupancy. The test should answer the following questions:

1. Is the CADR in the classroom reduced due to short circuiting?
2. How effective is the particle reduction in the occupied zone?
3. How are viruses of an infectious pupil distributed and reduced by the MAC?

4 TEST DESIGN

A classroom on the 2nd floor of the Zeppelin School in Speyer, Germany was selected for the test. A football team with boys of ages between 14 – 15 was hired. Test day was July 29, 2021, a sunny and windy day with 25°C. To fulfil the test scope the following test steps are planned:

1. To measure the infiltration rate during the test period, a tracer decay test with SF_6 is foreseen. SF_6 will be injected, distributed, and mixed before test start using a battery-powered leaf blower which is known from gardening.
2. To measure the effectiveness of the MACs, i. e. the removal of particles on the HEPA filter simulated by the adsorption of PFT on the active carbon a PFT decay test is planned. PMCH is injected, distributed, and mixed before test start. The PMCH will be removed by the active carbon in the same way as particles would be removed by the HEPA filter. Measured local PMCH decay rates multiplied by the classroom volume will lead to the Effective Clean Air Delivery Rate at every desk location in the room.
3. To simulate the dispersal of virus-laden particles in the room a constant flow of diluted PDCB is emitted at a selected location in the room with the start of test. PDCB mimics the particle emission of an infectious person in the classroom. From the measured local concentrations of PDCB the exposition to infectious particles can be calculated.
4. SF_6 and PMCH injection and mixing is done without the boy team in the classroom. After complete mixing is achieved the boy team is asked to enter the classroom and to take their seats.

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[1] NBC filter – nuclear, biological and chemical filters made of special active carbon material

5. Sampling commences for about 38 minutes.
6. Then the room air is mixed again by a leaf blower.
7. Test end is after 41 minutes

5 TEST PREPARATION

5.1 Determination of MAC flow rates

The Zeppelin High School in Speyer is under a preservation order. Due to the age of the building the ceiling heights are 3,50m which results in a room volume of 235m³ whereas average modern classrooms in Germany have ceiling heights of 3m and room volumes of approx. 200m³.
A German expert team (*VDI, 2021)* recommended that a MAC should be as efficient as a well-designed mechanical ventilation system which is capable to maintain good indoor air quality. This requirement is fulfilled if 35m³/h per person of fresh air is supplied to a room.

Applying this methodology to the average classroom with 25 pupils it will result in a CO_2 concentration increase of 660ppm. A MAC with a CADR of 875m³/h (25x35m³/h) will reduce particles in this classroom to 10% of its initial concentration within 31 minutes. The flow rate corresponds to an air exchange rate of 4,4h^{-1}, which shall be reached at every location in the occupied zone.

For the Zeppelin classroom with an average occupancy of 22 pupils and one teacher the CADR of the MACs corresponds to 805m³/h, a particle concentration reduction to 10% within 40 minutes and an air exchange rate of 3,4h^{-1}.

5.2 Classroom preparation

To reach the required 805m³/h it is decided to place 3 MAC units in the classroom with a speed of 270m³/h each. The locations of the 3 units are chosen by the schoolmaster under aspects of suitability (e. g. no obstacle for moving kids) and feasibility (e. g. location of plug sockets, cable routing) during normal school hours, see Figure 2.

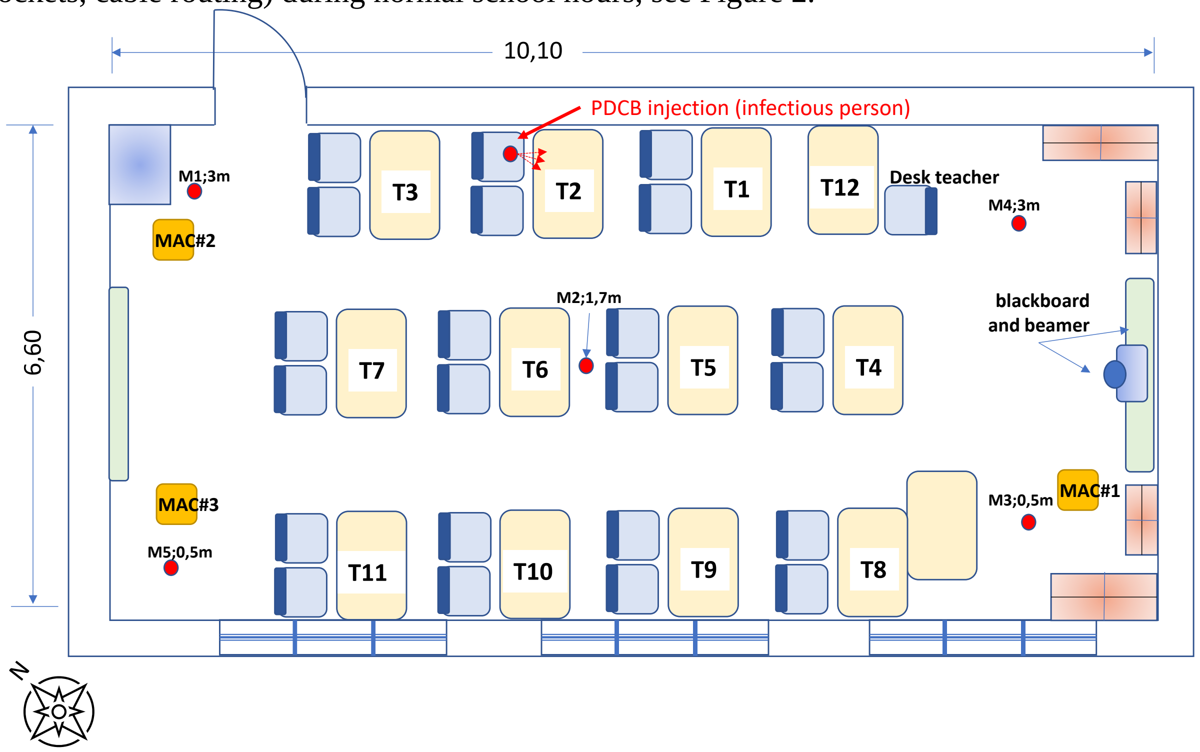

Figure 2 Schematic of classroom with mobile air cleaner positions and desks

5.3 Tracer gas test preparation

SF_6

One 60cc syringe is filled with 20% diluted SF_6 to measure the infiltration rate throughout the test interval.

PMCH

A 100µl glass syringe is filled with 80µl of liquid PMCH. To avoid that PMCH is evaporated into the classroom before test start the syringe was filled outside of the school building.

PDCB

A one litre lecture bottle (14bar) with 0,2188% PDCB in N_2 is prepared. A mass flow controller set the injection flow to 50ml/min. At this low PDCB concentration the injected gas has the same density as the room air and will not be affected by gravity. To mimic the real breath flow the end of a 1/8” tubing is taped to the chin of the person such that the injection gas is taken away with the breath of that person, see Figure 3.

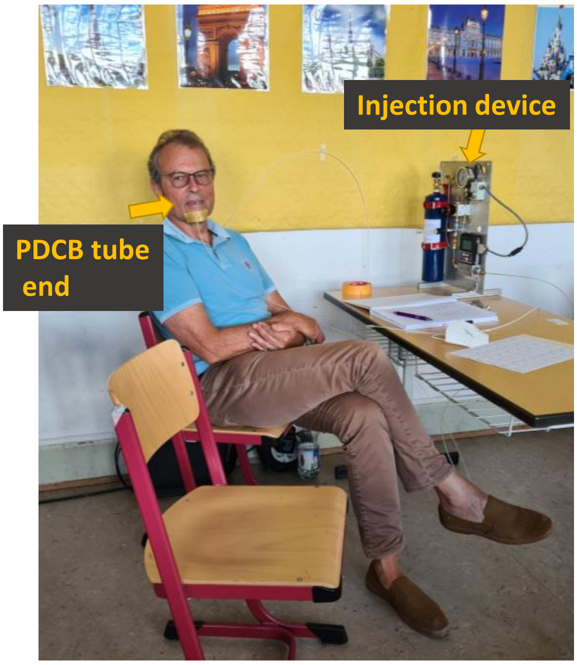

Figure 3 person who mimics the infectious pupil with the 1/8” PDCB injection tube end in front of the mouth; on the desk the injection device with lecture bottle and mass flow controller

5.4 Preparation of occupants

The boy team was instructed about the test procedure and handling of syringes. To cover the entire occupied zone of the classroom every boy was asked to take air samples in syringes at his desk. 10 syringes were placed on every desk and labelled with desk ID and numbers from 1 to 10. The boys are instructed to start sampling on command. Due to the turbulences of air in a room it is decided to take 2-minute average concentrations rather than to fill the syringes rapidly. The following 2 minutes are used to prepare for the next sample. In total ten 2-minute average samples are taken at every desk with pauses of 2 minutes in between. Correct sampling is exercised with the boys prior to test start. Joking of boys and incorrect sampling was also observed and corrected, However, it can’t be assured that every sample was taken correctly.

5.5 Preparation of additional sample locations

Further sample locations are installed at the inlet and outlet of each MAC. It is important to monitor PFT breakthroughs of the active carbon layer and to monitor short circuiting around the MAC. A 2m long 1/8" tube is positioned at the MAC in- and outlet and routed to a close-by sitting person. A 5cm long ¼" tube is connected at the end which perfectly fits to the Luer top of the sample syringe. Before taking a new sample, the tube is flushed. The sample frequency at the MACs is identical to the sampling at the desks.

6 TEST

6.1 Tracer gas injection

With no boys present in the room, room door and windows closed, the syringe with 20% SF_6 was injected while walking through the room. Parallel the micro syringe with liquid PMCH was emptied on a steel lid. During a walk through the classroom the few droplets evaporated quite fast. Then the room air was mixed for 15 minutes using the leaf blower.

To validate complete mixing of tracer with the room air five sample points, depicted in Figure 2 and marked with M and the height at the sampling location had been defined. Immediately after the samples are drawn the boys are asked to enter the classroom and to take a seat. This process lasts about 3 minutes.

6.2 Test start

Then the test is started, t = 0! All 3 MACs are turned on, no additional mixing in place. The injection of PDCB at the mimic person is started and sampling commences as described. Figure 4 shows a view into the classroom. One of the two boys to the front left is taking a local air sample while his neighbour takes samples from the MAC in the front via two sample tubes.

Figure 4 Sampling at all desks and all 3 MAC in- and outlets during the test

After test end the air MACs are shut off and the room air is again mixed with the leaf blower and another 5 samples are taken. This last sample is important to calculate the total amount of tracer gas in the room at the end of test to crosscheck the tracer gas balance between room and adsorbed mass in the MACs.

7 TEST RESULTS

7.1 Tracer gas SF_6

SF_6 is the tracer gas which is not affected by the operation of the MACs. It is used to measure the infiltration rate which also contributes to the dilution of particles resp. tracer gases. To calculate the effectiveness of the MACs in chapter 7.2 the infiltration rate needs to be subtracted.

The validation of complete mixing at the locations M1 to M5 in the room shows a mean concentration of 37,6ppb with a standard deviation of ±0,3ppb indicating that the tracer gas is perfectly mixed. Because it is difficult to keep 14–15-year-old boys calm it was decided to do the mixing without the pupils and to ask them in after mixing is achieved. It took 3 minutes to get the pupils in with the classroom door open. This resulted in a local displacement of the start concentrations at every desk due to cross ventilation, as depicted in Figure 5.

The local air change rates are almost equal and amount to $0,17h^{-1}$ with a standard deviation of $0,03h^{-1}$. The infiltration flow is $40m^3/h$. In view of the large flow rates of $810m^3/h$ induced by the MACs the correction due to infiltration is in the order of 5%.

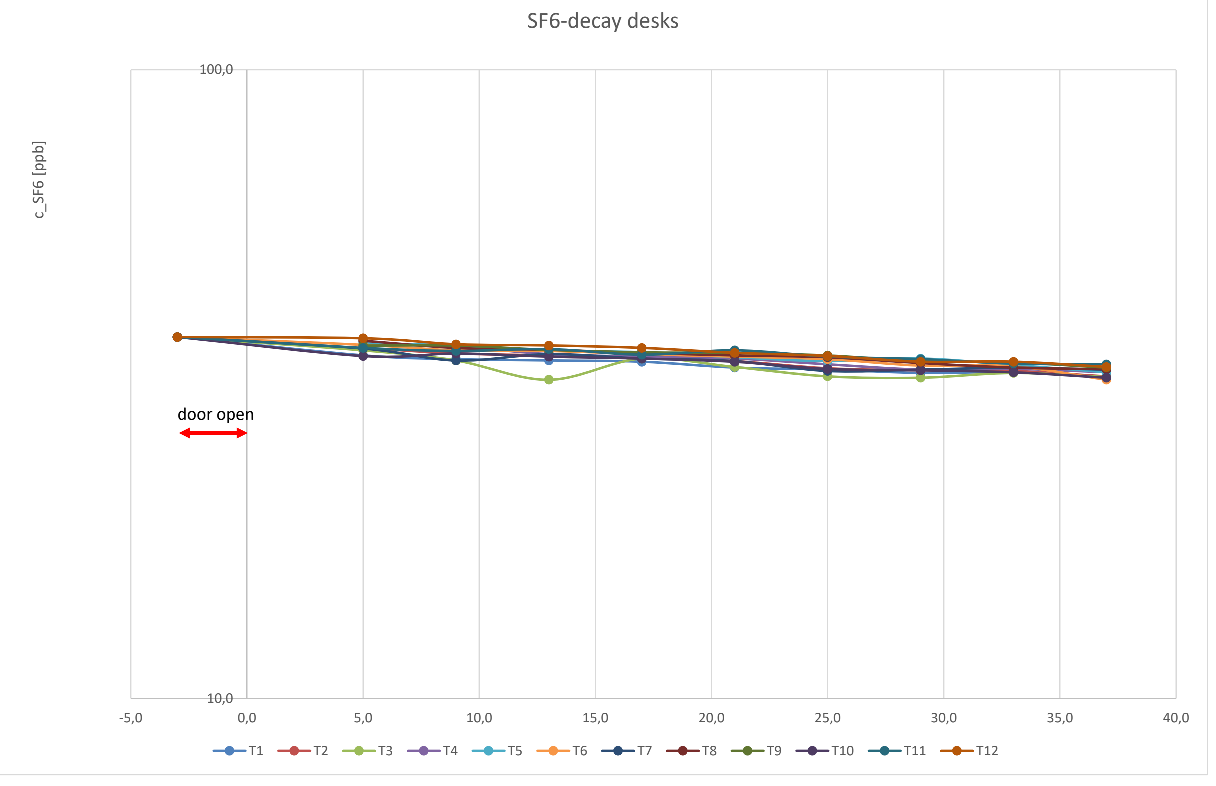

Figure 5 SF_6 decay test to measure the infiltration into the classroom

7.2 Tracer gas PMCH

Prior to the test in the Zeppelin School the adsorptivity of one UniqAir PRO device was tested for different Perfluorocarbon tracer gases and SF_6 at various fan speeds. PMCH showed at a flow rate of 270m³/h a filter efficiency of approx. 98-99%, PDCB >99% and for SF_6 it was zero.

For PMCH the initial mixing is good as expected, showing a mean concentration at M1 to M5 of 42,01ppb with a standard deviation of 0,71ppb (1,7%).

The local PMCH decay concentrations at all 12 desks (solid lines) as well as the inlet concentration at all 3 MACs (dashed lines) are shown in Figure 6. The local displacement of the first concentration reading at t=5min as described before for SF_6 can be observed here again. The mean of all desk PMCH decay rates are 2,91h^{-1} with a standard deviation of 0,16h^{-1} (5%). The PMCH decay rate includes the operation of the 3 MACs and the effect of infiltration. To determine the effectiveness of just the 3 MACs the infiltration is subtracted. Therefore, the cleaning rate due to the sole operation of the MACs is 2,74h^{-1} corresponding to an Effective CADR in the classroom of 644m³/h instead of the envisaged 810m³/h.

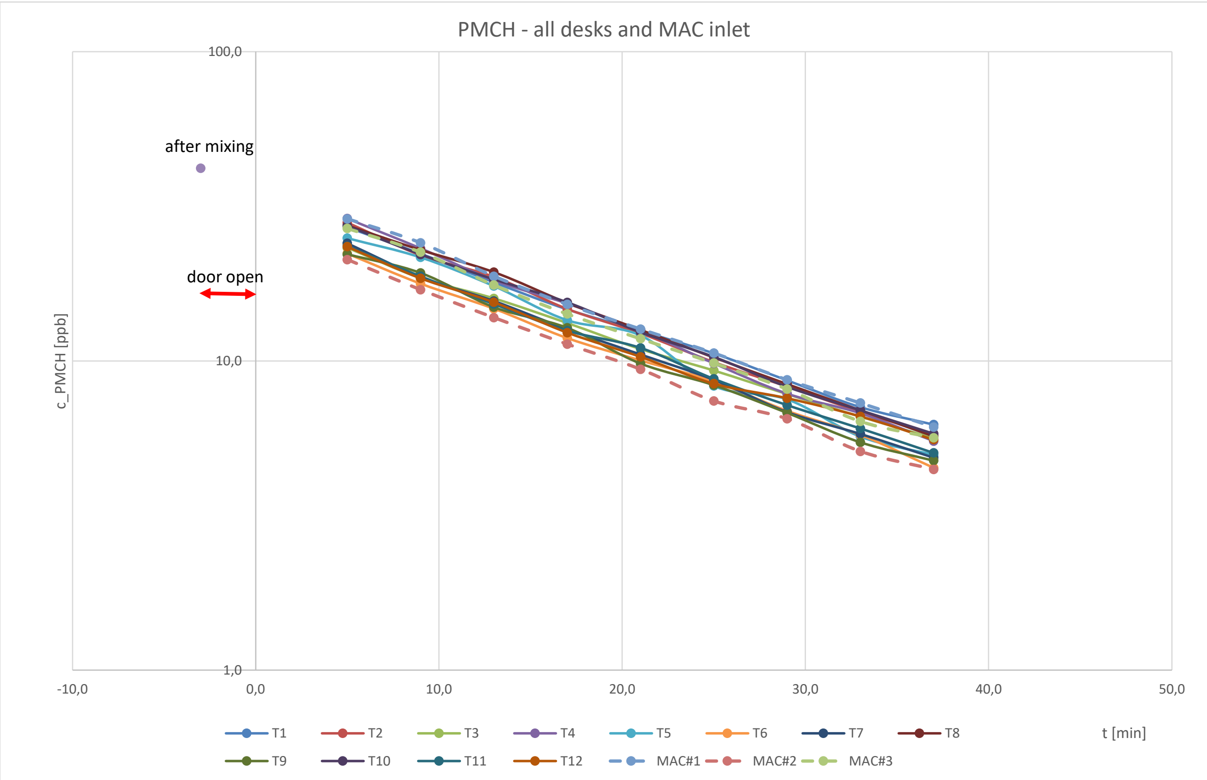

Figure 6 PMCH decay curves at desks T1-T12 and MACs (dashed)

As the MAC outlet concentrations have been monitored too, it is possible to check the filter performance. The filter efficiencies for PMCH are not close to 99% as expected from the pre-tests, for MAC-#1 it is just 80,4%, for MAC #2 80,8% and for MAC-#3 only 52,1%.

After test end and analyses of all sample syringes it is assumed that the flanges of the cylindrical filters may have not been tight and allowed a bypass flow which enters the classroom unfiltered. This assumption is substantiated by a separate test with one MAC a week later. The filter manufacturer adopted an improved design to eliminate future leakage problems. It is also noticed that the scale to set the fan's speed is not linear and that the real flow at the set-point was 252m³/h instead of 270m³/h. This means that the measured Effective CADR of 644m³/h needs to be compared to 756m³/h (3x252m³/h), i. e. a performance loss of 15% due to leakage.

Due to the lower pressure drop across the filter the airflow increased to an unknown value.

A main reason for this test however was to measure if there are inefficiencies in form of short circuiting around the MAC. If the MAC inlet concentrations are lower than the concentrations in the occupied zone this is the indicator of short circuiting. Figure 7 shows that the mean concentrations of all desks (occupied zone) at a certain time are almost identical with the mean concentrations of the 3 MACs. From this result it can be concluded that the use of 3 small instead of one big Air Cleaner and the schoolmaster's placement of the MACs leads to a good purification of the occupied zone without any circuiting.

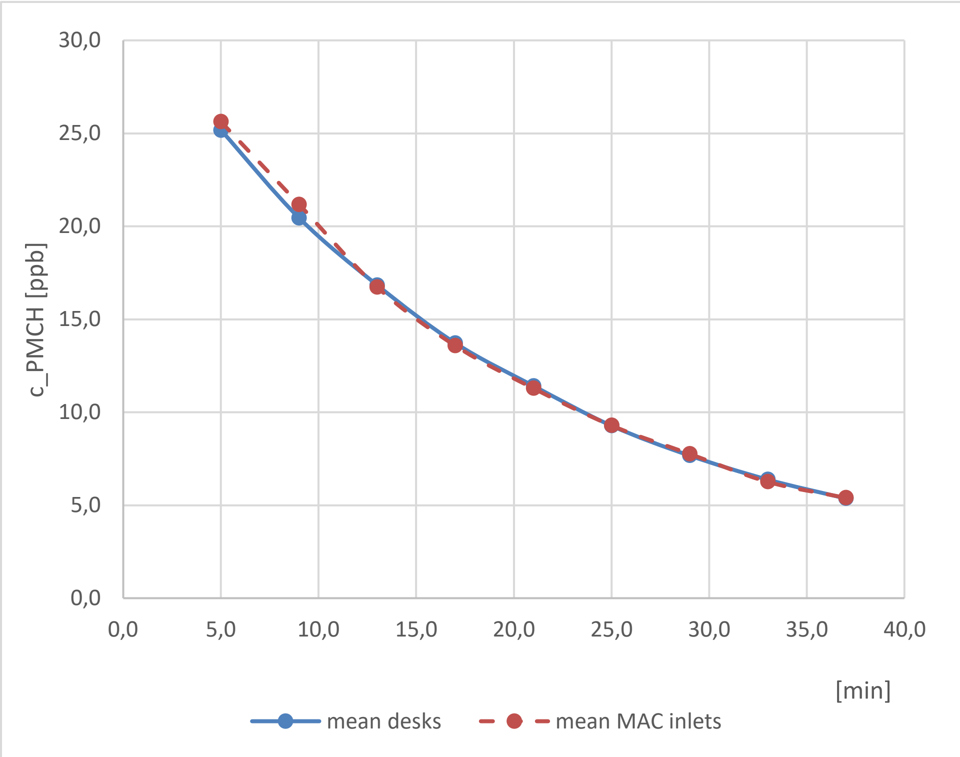

Figure 7 mean PMCH concentrations from all 12 desks versus mean inlet concentrations from 3 MACs

7.3 Tracer gas PDCB

The filter efficiencies for PDCB in this test are slightly higher with 82,7% in MAC-#1, 81,5% in MAC#2 and 60,3% in MAC-#3 compared to PMCH. The mean PDCB filter efficiency is 74,8%.

Due to constant injection of PDCB an increase in PDCB concentration is expected at all locations in the classroom. Measurement data shows Figure 8. The upper dashed line in black shows the theoretical concentration increase for an airtight classroom with complete mixing without a MAC operating. The dashed pink line below indicates the effect of additional infiltration. The fat dashed line in red shows the theoretical PDCB increase with infiltration and all 3 MACs operating with 252m³/h and 100% filter efficiency. The fat dashed green line shows the measured PDCB mean concentration from all desks.
All solid lines depict local PDCB increases at the desks of the pupils. After the test end the room air is again mixed using the leaf blower. This time the pupils stayed in the room, but it can be seen from the last concentration reading at 41 minutes that 5 minutes of active mixing is not enough to achieve a well-mixed zone.

Fluctuations in the local PDCB concentrations are observed which are due to air turbulence, occupancy, and MAC-fan effects.

If one calculates the theoretical PDCB increase at 252m³/h (fat dashed red line in Figure 8) not with 100% but with the measured mean filter efficiency of 74,8% the red dashed line shifts exactly to the green dashed line, which indicates consistency of the test results. It also leads to the conclusion that a UniqAir PRO without flange leakage will most likely achieve an Effectiveness in the occupied zone of 100% with no short circuiting.

From the data in Figure 8 it is possible to calculate the exposure at every desk. The exposure is the product of time and concentration a person is exposed to a contaminant. It is the area under the concentration curve for a certain location. Figure 9 depicts the exposition deviations from the mean exposure for all desks in the occupied zone. Due to the single MAC in the front of the classroom (right side) pupils have a higher exposure at tables T2, T1, T12, and T4 of up to 32% the maximum compared to the desks in the other parts of the classroom.

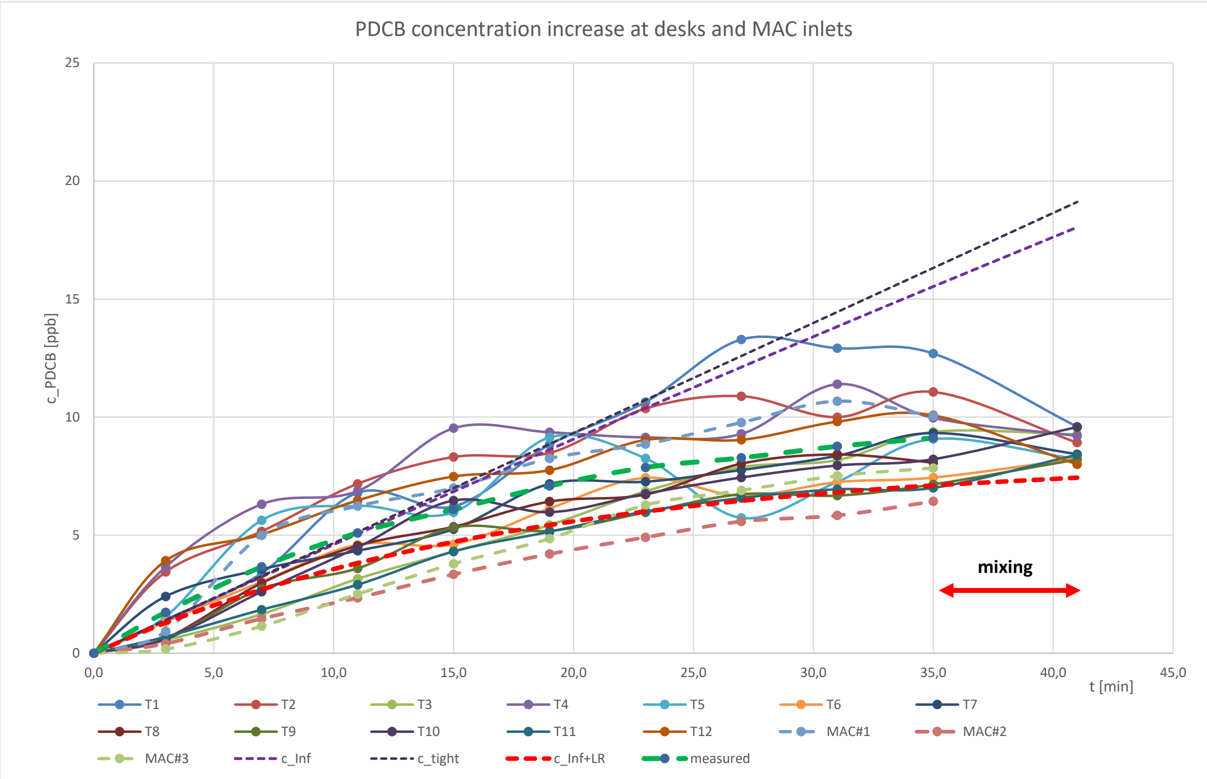

Figure 8 Increase of PDCB concentrations at desks

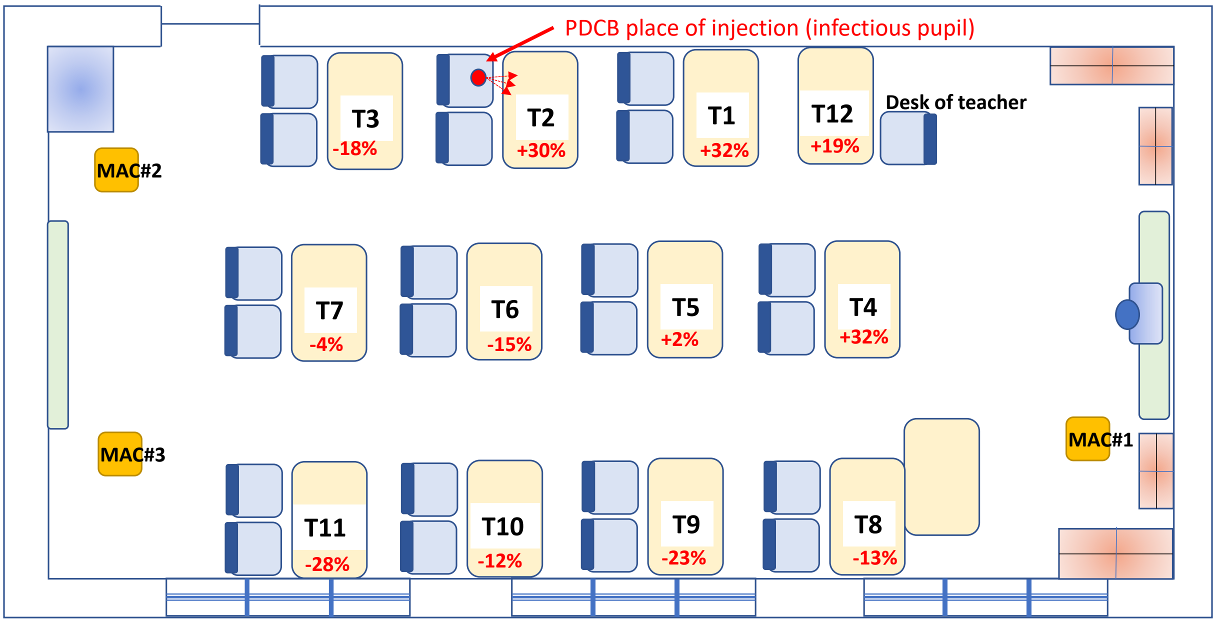

Figure 9 Relative exposition distribution for an emission source located at T2

8 CONCLUSIONS

The paper describes a test setup to measure the effectiveness of air cleaners in a real and occupied classroom. To get around the multiple uncertainties using aerosol generators with particle counters to measure the distribution and removal of particles in a real room, a tracer gas test with SF_6 and two perfluorocarbon tracers (PFT), here PDCB and PMCH, was introduced. The analyses of tracer gas concentrations with gas chromatograph with Electron Capture Detector makes it possible

- to inject tracer gases via simple 60cc syringes and/or small lecture bottles
- to sample at many locations at the same time
- to realize average sampling over a certain time interval
- to spend a minimum of effort for test set up with later syringe analyses in the lab.

As the test subject is the mobile air cleaner UniqAir PRO with a HEPA particle filter and an active carbon filter, use is made from the analogy, that particles are removed in the same way by the particle filter as PFT are removed by the layer of active carbon. By injecting PFT instead of aerosol particles it is possible to exclude uncertainties which are inherent to aerosol tests. Main uncertainties arise from the fact that particle counters can't differentiate between generated aerosol particles and particles already present in the room or generated by people activities and particle entry or exit via natural ventilation.

The decay of PMCH in the room is caused by adsorption in the 3 MACs and by infiltration. To determine the net removal rate due to the operation of the 3 MACs, the infiltration rate during the test was determined by a SF_6 decay test and subtracted from the PMCH decay rate. The chosen tracer gas technique made it possible to accurately quantify the performance of MAC in a real room in presence of natural ventilation.

Concentration measurements at the MAC inlet and outlet opening uncovers leakage around the filter flange which reduces the particle resp. PFT removal performance by 15%.

In case such a test is done with aerosol injection and particle counters it is essential to monitor not only the room but also the inlet and outlet concentrations to identify malfunctions like that. So many particle counters are usually not available in practice for one test.

The risk of short circuiting around a MAC gets bigger with increasing flow rate. Therefore, UniqAir favours to place more MACs with lower airflows in a room. Short circuiting is quantified by comparing the mean PMCH concentration in the occupied zone (all desks) with the inlet concentrations of the 3 MACs, which turns out to be completely identical throughout the test. This leads to the conclusion that despite the placement of the MACs in the 3 corners of the room the airflows flushed the occupied zone well and no short circuiting took place. The Effective Clean Air Delivery Rate in the classroom is the same as the CADR of the 3 MACs, although decreased by the filter leakage.

The risk of a SARS-CoV-2 virus infection depends on the number of infectious persons in the room, their location, their virus load, the airflow pattern, the time of contact, the vulnerability of the contact persons, and many other factors. In a real situation much of this information is not known. The local release of the PDCB tracer gas mimics the spread of viruses of one infectious person at a certain location. Sampling at every desk makes it possible to measure the individual exposure of every person in the classroom. Persons close to the location of release have exposures of +32% above average the maximum while others are smaller down to -28%.

This test substantiates the difference between a decay test with complete mixing at start and a constant injection test at a certain location. Both tests serve a different purpose. The draw conclusions from the results of one test to the other is not possible.

A consistency check with PDCB applying the measured filter efficiency due to leakage indicates that an improved MAC design without flange leakage will be to 100% effective in the classroom, although this could not yet be validated by tests.

9 ACKNOWLEDGEMENTS

Contracting body: TÜV Technische Überwachung Hessen GmbH, Frankfurt a. M. and Mika Wilska, German Distributor, Speyer of UniqAir Oy, Lappeenranta, Finland.

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