Suitability of ventilation panels for permanent reduction of CO2 levels in classrooms

by Peter Eyerer, Markus Palic, Klaus Weber and Udo Schmid*

Initial situation

Carbon dioxide (CO2) is a decomposition product of human respiration. Its concentration is regarded as a central indicator of indoor air quality in permanently occupied rooms and forms the key parameter for its assessment. In schools, high indoor air quality is an important prerequisite for the ability of pupils and teachers to be able to concentrate. Although the CO2 concentration is not directly related to the viral load, especially with regard to aerosols of SARS-CoV-2, a high air quality significantly reduces the risk of mutual infection of those present [1,2,3].

To improve indoor air quality in classrooms, starting from a pre-exposure of 300-500 ppm, when CO2 concentrations reach between 1000 and 1500 ppm, the windows and classroom door are usually opened for shock and/or cross ventilation in rooms without "room air handling systems". Ventilation can last from 5 to 15 minutes, depending on the size and occupancy of the classroom, as well as the amount of back pressure on the facade and the temperature difference between inside and outside [3]. During this process, lower outdoor temperatures cause temporary cooling of the classroom, which is usually compensated for after a few minutes by the heat stored in the walls and furniture, as well as the heat emitted by those present. Another way to reduce CO2 concentrations is through permanent or sporadic tilt-up ventilation of tilt-up windows where classrooms have them.

An alternative to manual sporadic window or permanent tilt ventilation is facilitated by ventilation panels, which are installed in the windows in exchange for one or more window panels and permit permanent cross ventilation. The "ventilator window" is arranged in such a way that, if possible, ventilation occurs along the diagonal of the room. In this way, the preheated and less pre-polluted corridor air can be drawn in through the partially or fully opened classroom door and conveyed to the outside by the panel's fans. A permanent, at least partial opening of the classroom door is an indispensable prerequisite for this.

The article shows the results of a real-life test, in which the effectiveness and properties of the AirContinui© ventilation panel from Brach & Gräßer for continuous reduction of the CO2 content in a non-air-conditioned and non-automatically ventilated classroom as an alternative to push or tilt ventilation were investigated.

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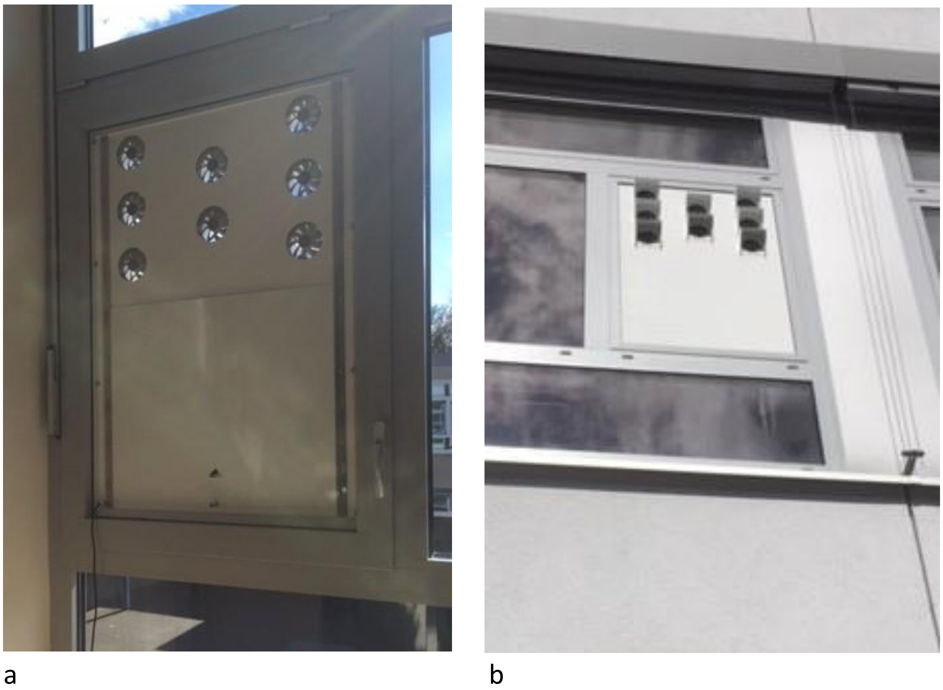
Construction and operation of the ventilation panel

The panel used for measurement consists of an opaque sheet metal and plastic construction. It has 8 recessed fans with an operating voltage of 12 V, a measured total electrical power consumption of 7.5 W and a sliding shutter so that the ventilation area can be closed. A tightly woven stainless steel wire mesh attached to the exterior prevents the unwanted entry of insects. The panel was individually manufactured in the dimensions of the glass pane to be replaced. The window sash fitted with the panel can be both fully opened and tilted (Fig. 1).



a b

Figure 1. Ventilation panel "AirContinui" - interior view (a) and exterior view (b)

Test setup and execution

Prior to the measurements, the manufacturing company arranged for the glass pane in one of four casement windows in a standard classroom of a Karlsruhe comprehensive school with a free flow cross-section (in open condition) of approx. 1 m^2, to be replaced by the ventilation panel to be tested. The room corresponds to an average classroom for a maximum occupancy of 30 pupils*. With a window front length of 9.53 m, a width of 7.2 m and a height of 3.16 m, it holds a volume of approximately 217 m^3, or 7.3 m^3 per pupil at full occupancy. This is above the minimum air volume of 6 m^3 per pupil as specified in the literature [4].
The measurements were carried out with 12 test persons (9 pupils and 3 adults) over a period of approx. 4 hours during regular lessons and during a written examination lesson.

Three CO2 loggers, SA 1200P from Conrad Elektronic SE, a weather station, CTW-902 Wi from Sainlonic on the roof of the building, a commercial anemometer for recording the air flow in the classroom, a sound level meter and two CO2 traffic lights, a V2 from FabLab Karlsruhe e. V. and a CO2A 100 from MB-Systemtechnik were used for the measurements.

Prior to the regular CO2 measurement, both a sound level and a wind speed measurement were performed in the unoccupied state of the classroom. With the fans in full operation, the sound measurement at a distance of 2 m, the closest seat of a test person to the fan window, resulted in a value of 43 dB. The manufacturer specifies the sound pressure level of a single fan as 40 dB. When the sound level measurement was repeated with an occupancy of 13 test subjects, only marginal changes resulted compared to the unoccupied classroom. Here, the sound pressure level of background noise within the classroom predominated.

The wind speed measurement dropped below the anemometer's response limit of 0.1 m/s at a distance of less than 20 cm from the center of a fan. Even at this short distance from the panel, no draft was perceptible.

Measurements of the CO2 concentration trend were made in three runs. When arranging the three CO2 loggers in the classroom, care was taken to measure the pollutant concentration at different points in order to obtain a representative average value in the event of presumably different concentrations in the different parts of the room.

One logger was placed on the first school bench next to the classroom door, the second on a school bench in the windowless "dead corner," and the third on the window sill diagonal to the classroom door (Figure 2). At all three measurement points, the distance to a subject was at least 1.5 m. The subjects recorded the results of the measurements in measurement tables with a recording frequency of 5 minutes. The inertia of the measurement instruments was taken into account when determining the measurement frequency.

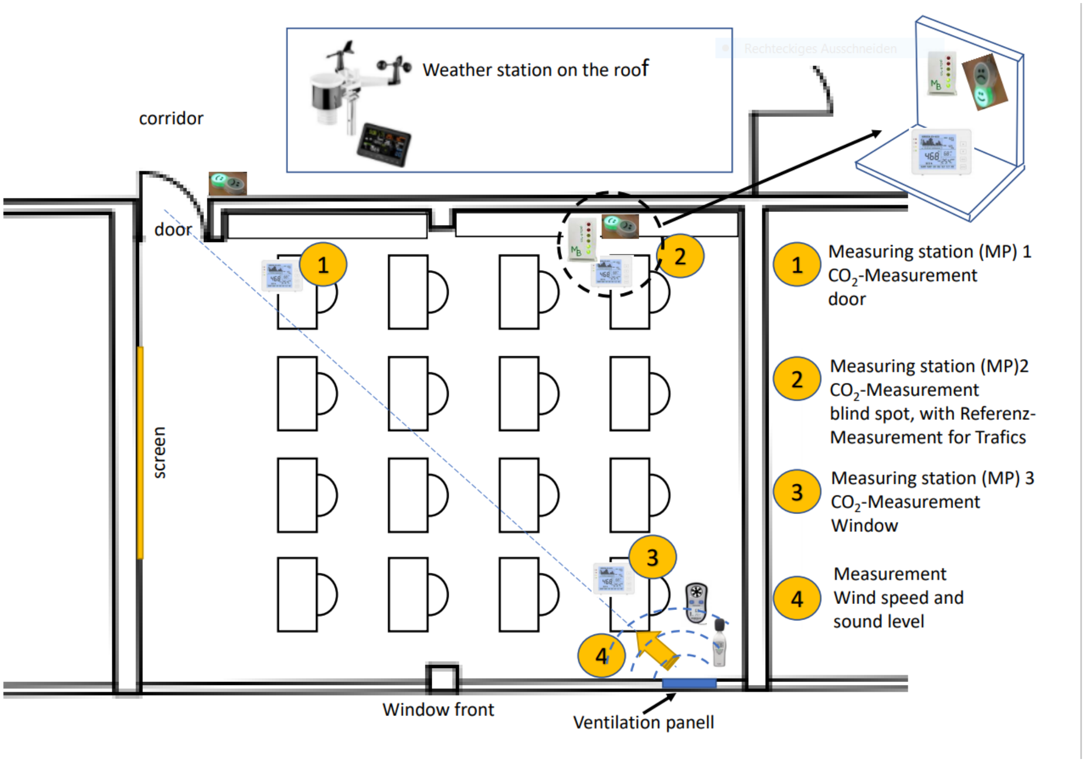


Figure 2. Schematic representation of the classroom with the various measurement points.

Evaluations

The first of three measurement runs was performed with the windows and classroom door closed as a "reference scenario" to determine the CO2 concentration trend in the room without ventilation. During the test run, wind speeds of 0.7 to 2.2 km/h prevailed from alternating directions, so that a hermetically sealed classroom without significant joint ventilation can be assumed as a good approximation.

The first measurement over 25 minutes started at 539 ppm and ended when the CO2 concentration reached about 1000 ppm at measurement point 2, where the CO2 traffic lights were also placed (blind spot). The average CO2 concentration from the three measurement points in the room at this time was 933 ppm. After 5 minutes of shock ventilation, during which the mean concentration in the room dropped to 588 ppm, the windows and doors were closed again and kept closed until the critical value of 1500 ppm was reached at measurement point 2. The CO2 concentration curve of the first run is shown in Figure 3, red dots. As expected, the highest value comes from measuring station 2 (dead angle), the lowest value from measuring station 3 (near the window) and the value in between from measuring station 1 (near the door). The curve shown in red follows the arithmetic mean values of the measurements at the three measuring stations.

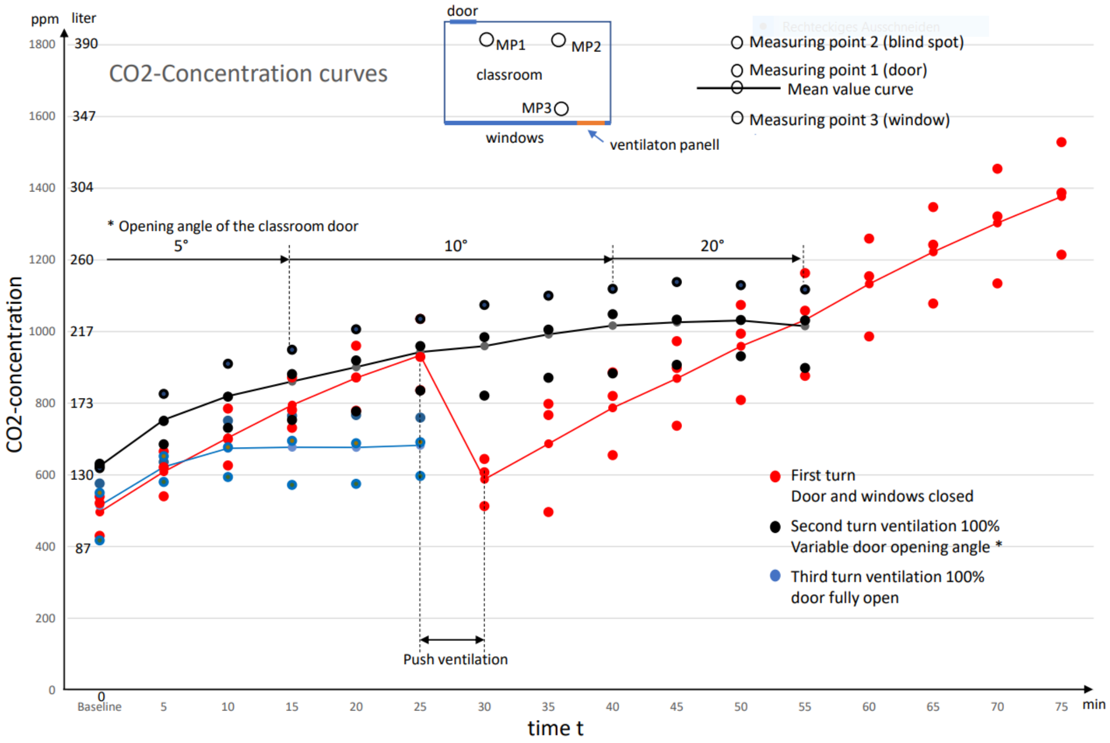


Figure 3. CO2-concentration curves in the classroom during the experimental measurements in the three runs. Each run starts at time t=0

To calculate the concentration course, the initial and final values of the CO2 concentrations are converted to liters (l). Consequently, 497 ppm (mean initial value before the first run) corresponds to 0.0479 vol. % and taking into account the total room volume of 217,000 l, to an initial concentration of 108 l of CO2.

The measured increase in concentration (progression) in the closed classroom results from the first partial measurement in the first run to:

CO2KM = (KCO2 E - KCO2 A)/t = (202 l-108 l)/25 min = **3.8 l/min** {1}

Where:

CO2KM	measured increase in concentration of CO2 in l/min
t	duration of measurement in min
KCO2 E	final concentration after t in l
KCO2 A	Initial concentration at start of measurement in l

From the second partial measurement follows:

(289 l-127 l)/45 min = **3.6 l/min**

Both measurements come to almost the same result. In this respect, it can be concluded that these are valid CO2 progressions related to this room and the number of test persons present.

The **expected** progression is calculated by the number of subjects and their specific CO2 emissions caused by breathing. In [6] and [7] the following exhalation values can be found:

Breathing rate 1/min	Breathing volume l/1	CO2 emission %.	
Pupils 20	20	0.4*	4
Adults 15	15	0.5	4

* In the literature, 350 ml is given as the respiratory volume for schoolchildren. Since the subjects were grade 10 pupils, the breath volume was slightly increased to 400 ml.

In all runs there were on average 9 pupils and 3 adults in the room. Accordingly, the following increase in concentration would be expected:

CO2KR = nP. x AF x AZV x CO2A = 9 pup. x 20 1/min x 0.4 l/1 x 0.04 = **2.9 l/min pup.** {2}

= 3 ad. x 15 1/min x 0.5 l/1 x 0.04 = **0.9 l/min ad.** {3}

Where:

CO2KR	calculated increase in concentration of CO2 in l/min
nP	Number of persons
AF	Respiratory rate in 1/min
AZV	Breath volume in l/1
CO2A	CO2 output per breath in %.

The total calculated concentration increase is CO2KR **= 3.8 l/min**. The measured and the calculated CO2 progressions show an extremely high correlation and serve in the following as a reference value for the measurement runs with the active ventilation panel.

Measurements with active ventilation panel

In the second run, the effectiveness of the ventilation panel operating at full power was measured at different opening angles of the classroom door (Fig. 3, black dots). Again, the higher readings show the concentration at measurement point 2, the blind spot, which is measuring point near the window, the lowest and the measuring point near the door the values in between. The black curve shows the course of the arithmetic mean values of the three measuring points.

During the first 15 min, the opening angle was 5°. Here, the increase in concentration was initially almost parallel to that without ventilation. Although the flow cross-section of the narrow door gap corresponds to many times that of the fan ensemble in the panel, it was not sufficient for effective ventilation. Only during the subsequent 25 min, at an opening angle of 10°, did the progression flatten slightly which serves as an indication that some degree of ventilation occurred. Only after the room door was opened to 20° KOMMA? after KOMMA?40 min did unobstructed ventilation begin, which, as will be seen in the third run, did not increase further even with the door fully open. The flat curve in this measurement sequence indicates that the "cleaning power" of the panel is sufficient to prevent further progression of the CO2 concentration at the present room size and occupancy. In the last measurement sequence (door 20° open) in this run, the following concentration progression results mathematically.

$$\text{CO2PM} = (\text{KCO2 E} - \text{KCO2 A})/t = (224\ \text{l} - 227\ \text{l})/15\ \text{min} = \mathbf{-0.2\ l/min} \qquad \{4\}$$

Accordingly, over this measurement sequence, the CO2 concentration in the room decreased minimally. Thus, the purification efficiency at this concentration level is:

$$\text{CO2GES} = \text{CO2KR} - \text{CO2PM} = 3.8\ \text{l/min} - (-0.2)\ \text{l/min} = \mathbf{4.0\ l/min} \qquad \{5\}$$

CO2GES: determined reduction of CO2 concentration in the room in l/min.

For the third run, after a longer pause in ventilation, as well as a decrease of the mean CO2 concentration in the room to 514 ppm, the classroom door remained fully open, and the ventilation panel operated at full load during the run. Plots of the measurement results from this run are shown in Figure 3 as blue dots in the same manner as in the first two runs. The mean CO2 concentration increase rises sharply at first and then visibly flattens out. Already after 10 min it changes into a parallel run with the abscissa, similar to the curve from the last section of the second run, and confirms the assumption that the ventilation panel in the present dimensioning is just sufficient to compensate for the CO2 concentration increase taking place without ventilation in the selected classroom and the number and type of subjects participating in the experiment. In the case of a smaller room or a higher number of occupants, a higher cleaning capacity should be provided.

Measurement results and evaluation

The individual curves show a striking increase in the ability of the ventilation panel, referred to here as cleaning power, to counteract the increasing CO2 concentration in the room. This is clearly evident at the start of each measurement. Regardless of whether with or without fan operation, the CO2 concentration first increases rapidly at a low concentration level in the room. As the absolute concentration increases, so does the cleaning performance of the panel. However, a serious, quantitative statement on this phenomenon is not possible according to the available measurement tests. For a more accurate assessment, the measurement frequency in the initial phase of the measurements is too low and the reaction time of the measuring devices used is too long.

In order to compare the effectiveness of shock ventilation and forced continuous ventilation by the ventilation panel, the air exchange rates are calculated below from the measurement results and the manufacturer's specifications for both variants.

The ventilation performance of the panel can be determined by the air flow. The manufacturer specifies this as 66.3 m^3/h per fan. The open screen area of the insect screen is 42% and reduces the airflow accordingly. Accordingly, the effective air flow is 27.8 m^3/h per fan and, with 8 fans, 222.8 m^3/h of the panel used. At 217 m^3 room volume, the air exchange rate is about 1/h.

The air exchange rate due to the 5-minute shock ventilation in the first test run can be determined from the CO2 concentration change during ventilation using the mixing formula. The following applies:

VR x KE = VV x KV + VF x KF {6}

Where:

VR	Room volume of the classroom in m^3
KE	CO2 concentration in the room at the end of the ventilation break 588 ppm
VV	Volume of the used, transported out of the room air in m^3
KV	CO2 concentration before the ventilation break 988 ppm
VF	Volume of fresh, inflowing room air in m^3
KF	CO2 concentration in fresh air 350 ppm

Resolved according to the calculated fresh air volume VF in the room, the following follows after 5 min:

VF = VR x (KV - KE) / (KV - KF) = VR x (988 ppm - 588 ppm) / (988 ppm - 350 ppm) = VR x 0.62

Extrapolated, the **air exchange rate** is approximately **7.5/h.**

Heat balance

Assuming that a 5-minute push ventilation is carried out once per school hour to reduce the CO2 concentration, the fresh air flowing in must be heated to the temperature level of the interior, regardless of the heat storage capacities available in the room. The following amount of heat is required for this [8]:

With the shock ventilation: QS = LS x VR x ϱair x CLuft x (ϑI - ϑA) {7}

With the ventilation panel: QP = LP x VR x ϱair x CLuft x (ϑI - ϑF) {8}

Where:

QS	required heat quantity during shock ventilation in kWh
QP	required heat quantity for panel ventilation in kWh
LS	Air exchange rate during shock ventilation 0.62 in 5min
LP	Air exchange rate during panel ventilation 0,77 in 45min
VR	Room volume 217 m^3
ϱair	Density of air 1,19 kg/m^3
CLuft	Storage capacity of air 0.00028 kWh/kgK
ϑI	standard internal temperature 20 °C
ϑA	Mean outdoor temperature during the heating period 3.3 °C (long-term average).
ϑF	Corridor temperature* 13 °C

* The standard temperature for corridors and staircases is 15 °C. In the following calculation, the operation of ventilation panels in all classrooms is assumed to lower the corridor.

For the 5-minute push ventilation, this results in a heat quantity of

QS = 0.62 x 217 m^3 x 1.19 kg/m^3 x 0.00028 kWh/kgK x (20 °C - 3.3 °C) K = **0.74 kWh,**

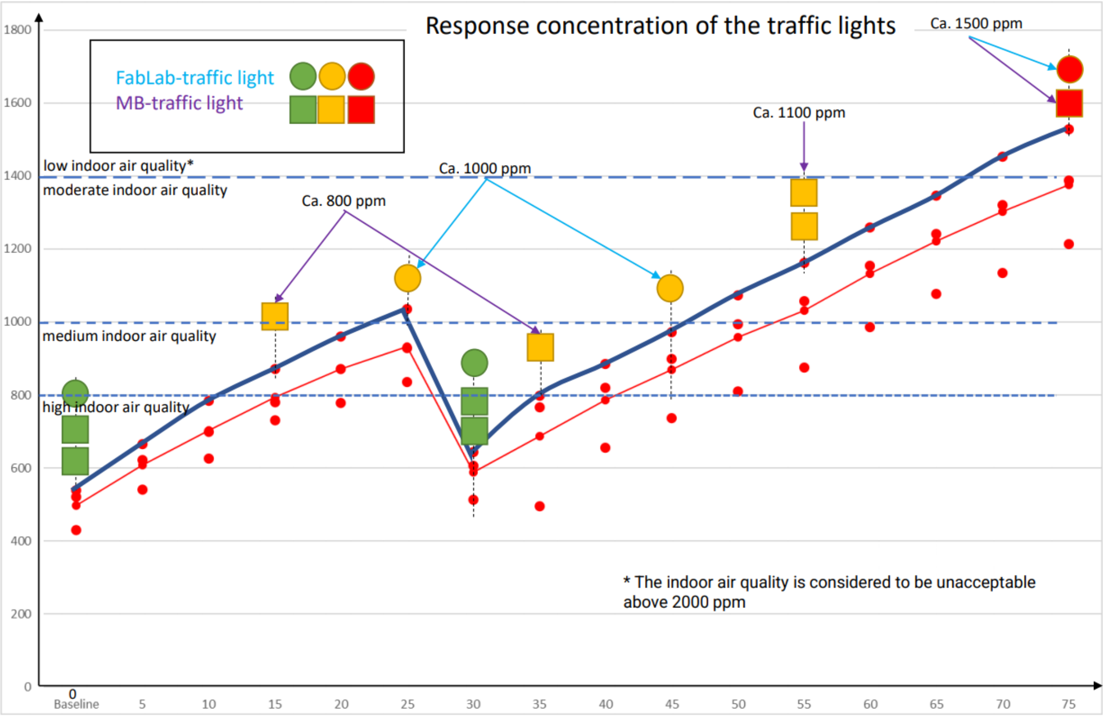
and for the 45-minute panel ventilation a heat quantity of

QP = 0.77 x 217 m^3 x 1.19 kg/m^3 x 0.00028 kWh/kgK x (20 °C - 13 °C) K = **0.39 kWh**.

Consequently, the amount of heat needed to heat the air flowing in, under the previously mentioned condition that the corridor temperature remains at 13 °C, is about half of that needed for shock ventilation.

Test of the CO2 traffic lights

During the first run, the readings of the CO2 traffic lights were recorded as well (Fig. 4). In addition to the CO2 logger measurement, measurement station 2 (blind spot) also included recordings of the operation of the two traffic lights that were also tested.



* The indoor air quality is considered to be unacceptable above 2000 ppm

Figure 4. Display of the CO2 traffic lights in the first test run

The FabLab traffic light display consists of two circular light indicators, one of which is both green and yellow (with a happy smiley) and the second is red (with a sad smiley). The thresholds are about 1000 ppm for switching from green to yellow and about 1500 ppm for switching from yellow to red.

The MB traffic light has two small luminous displays each for all three colors. The threshold values are more differentiated here. Already at approx. 800 ppm, the traffic light jumps from green to a yellow display. At approx. 1100 ppm, the second yellow light also lights up. At 1500 ppm it jumps to a red display. It could not be determined at which concentration it switches to double red since the experiment was terminated when 1500 ppm was reached. Already at about 1200 ppm, pupils occasionally felt the need to open the windows.

In the relevant literature [1,2,4], air quality is described as high at CO2 concentrations up to 800 ppm, medium up to 1000 ppm, low up to 1400 ppm (in some literature also 1500 ppm), and unacceptable above 2000 ppm. In this respect, both tested traffic lights meet the requirements very well.

Results and conclusions

The measurements and calculations of the "cleaning performance" of the ventilation panel result in a room air exchange rate of approx. once per hour under the selected test conditions with eight fans used and a calculated "compensation effect" of 4 l CO2/min under these conditions. With a pupil-specific output of 0.32 l CO2/min from {2}, the continuous stay of approx. 13 pupils is possible with the present fan dimensioning without shock or tilting ventilation. Thus, one fan in the performance class installed here would be required for every approx. 1.6 pupils. From this the determining equation for the number of fans is as follows:

$$nV28 \approx nS / 1.6 \qquad \{9\}$$

or in general:

$$nV \approx 1750 \text{ x } nS / (v\dot{V} \text{ x } AS) \qquad \{10\}$$

Where:

nV28	required number of fans (free air flow 28 m^3/h)
nV	required number of fans in general
nS	number of pupils
$v\dot{V}$	Air flow per fan in m^3/h
AS	Open screen area (transmittance) of the insect screen in %.

Conditions of application for the equations:
The calculation formulas apply to pupils* in the upper grades (grades 10/11) and a specific room volume of approximately 7 m^3/pupil*. Due to the observed effect, according to which the cleaning performance increases with increasing CO2 concentration level, there could be a degression effect for the determination of the number of fans. However, no serious indication of this can be derived from the tests carried out. In this respect, dimensioning via equation {10} is always on the safe side. The equations are cut size equations, therefore the individual sizes must be used in the specified units.

Any aerodynamic shadowing effects of the fans on each other are likely to be negligible and are not taken into account here. When using fans with a higher air flow and/or when using an insect screen with a higher transmittance, the number of fans can be reduced accordingly {10}.

Summary

In three experimental runs, the effectiveness and characteristics of the ventilation panel "AirContinui©" by Brach and Gräßer were tested in an average classroom of a Karlsruhe school. The reference value for the increase in concentration was the first test with closed windows and closed classroom door as well as a 5-minute shock ventilation after a teaching period of 25 min. After the ventilation break, the experiment ran until the critical concentration of 1500 ppm was reached. This showed the typical "sawtooth curve" outlined in much literature. In the second experiment, the classroom door was opened gradually during panel operation and the degree of opening at which the CO2 concentration stopped rising was determined. The third experiment took place with the door open from the beginning and the panel active until the CO2 concentration also stopped increasing.

The ventilation panel in the present dimensioning with 8 fans and an air flow of 28 m^3/h each, reduced by 58% due to the insect screen, was able to keep the CO2 concentration permanently below 1000 ppm with a reduced occupancy of 13 persons, a number determinded by current COVID-19 regulations. The prerequisite for this was a standard classroom door with dimensions of 1m x 2m that was open by at least an angle of 20°.

The air drawn in from the corridor area, preheated in the heating season and precooled in the summer season, is led over the diagonal of the room to the ventilation panel and blown out. In this way, the ventilation panel continuously compensates for the CO2 concentration caused by the breathing of the occupants.

Based on the test results, a general calculation scheme for panel dimensioning for variable occupancy rates is derived and presented. Based on this, the number and airflow of fans for rooms with higher occupancy rates can be determined.

In the heat balance for heating the air flowing in, the ventilation panel shows a clear advantage due to the intake of preheated corridor air compared to impact ventilation with open windows and the cold outside air. The heat requirement for ventilation with the panel is half that for shock ventilation.

The CO_2 traffic lights from FabLab e. V. Karlsruhe and MB Systemtechnik, which were also tested in the trial, provide correct ventilation indications for the limit values of 1000 and 1500 ppm given in the literature.

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