Demand Controlled Ventilation in Schools – Energetic and Hygienic Aspects

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Keywords

Demand Controlled Ventilation, Indoor Air Quality, Mould Problems, Bacteria Concentration, CO_2 Concentration

Synopsis

In this study, we investigated the indoor air quality (IAQ) in classrooms with exhaust ventilation systems and in naturally ventilated classrooms. In the latter, we found peak CO_2-concentrations of more than 4000 ppm. 1500 ppm was exceeded during 40 to 86% of teaching time, dependent on class size. The windows were opened rarely in winter which led to low mean air exchange rates of 0.20 – 0.23 h^{-1}. The operation of mechanical ventilation systems improved IAQ considerably. Peak CO_2-concentrations decreased to less than 2500 ppm. 1500 ppm was exceeded for only 7 to 57% of teaching time. Mean air exchange rates of 0.36 – 0.41 h^{-1} were determined. The higher air exchange rates caused no measurable increase in heating demand. With respect to mould problems, no significant amount of viable airborne fungi was found. This didn't change if children were present. The viable airborne bacteria concentration increased during the lessons. No difference in viable airborne bacteria concentration was found in mechanically and naturally ventilated classrooms as long as the windows were closed. Results indicate, that wide opened windows in naturally ventilated classrooms may increase viable airborne bacteria concentration due to air turbulence, but this is to be investigated further. The acceptance of the mechanical ventilation systems by the teachers was very good. No problems with draught or noise were reported.

List of Symbols

n	air exchange rate [h^{-1}]
N	number of people in classroom
P_f	fan maximum electric power [W]
P_s	fan specific electric power [Wh/m^3]
Q	heat consumption [kWh/week]
U	heat transfer coefficient [W/m^2K]
$\dot{V}$	air flow rate [m^3/h]
V_r	room volume [m^3]

1 Introduction

In Germany, local governments usually don't financially support the installation of ventilation and air conditioning systems in public buildings, like schools. Exceptions may be rooms with high noise pollution requiring permanently closed windows or rooms in which toxic

substances are handled. According to the authorities, the necessary amount of fresh air in most cases can be supplied by natural ventilation. This is supported by an official guideline [1] of the AMEV, a union of engineers with the task to support the municipal building departments through "...continuous exchange of views and competent recommendations" [2]. Taking into account this attitude and the usually tight budget of communities, it is not surprising that only a few school buildings are equipped with mechanical ventilation systems.
In this work we present results obtained in a study on the energetic and hygienic aspects of demand controlled ventilation systems in a school.

2 The ventilation systems

Site of our investigations was an elementary school in Randersacker near Würzburg, Germany. The school is located at the edge of the town near the slopes of vineyards, so there aren't any problems due to noise or outdoor air pollution. We installed four exhaust ventilation systems in nearly identical classrooms (see Figure 1).

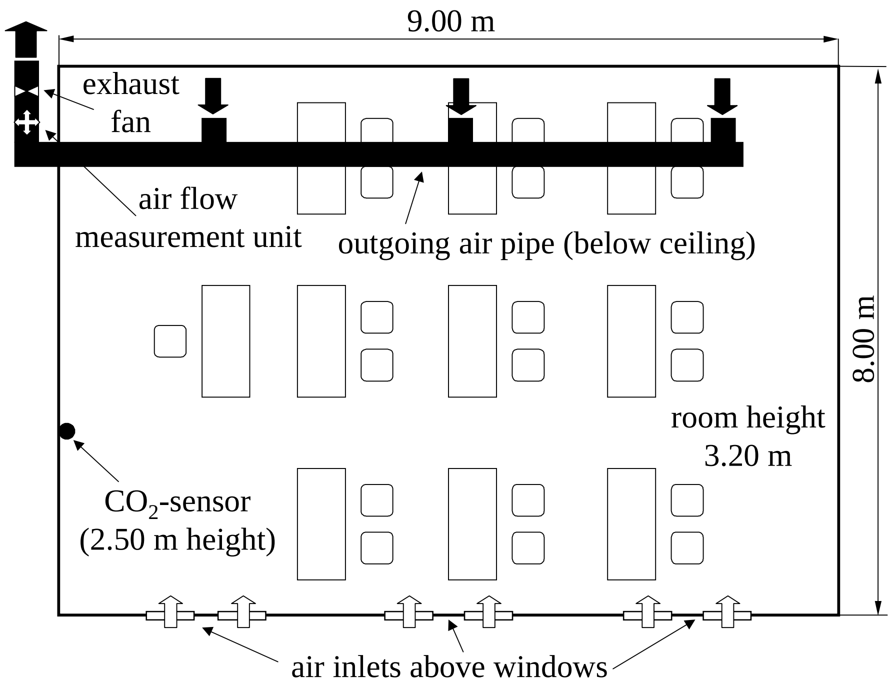

Figure 1: Installation scheme of exhaust ventilation system.

The ventilation systems have no heat recovery to keep costs low. Each system consists of six air inlets above the south facing windows and an outgoing air pipe with three valves. The exhaust fans are positioned outside the classrooms and can be controlled separately for each room via CO_2-sensors (Vaisala GMW22 with an accuracy of ± 20 ppm + 1.5% of measured value). For determination of air flow rates, we used constant air flow measurement units (Halton MSD100 with an accuracy of ± 5% of measured value for air flow velocities ≥ 4 m/s) in the outgoing air pipes. They achieve full accuracy for air flows greater than 113 m^3/h. Table 1 summarises the relevant parameters of the ventilation systems.

Table 1: Relevant parameters of the ventilation systems.

V_r [m^3]	N	$\dot{V}_{max}$ [m^3/h]	n_{max} [h^{-1}]	P_f [W]	P_s [Wh/m^3]	Cost [•]*
230	17-25	240	1.04	27	0.113	2000

*costs are per room and include material + installation (according to [3]).

The following air quality measurements were performed during November 22nd 1999 to February 25th 2000.

3 Indoor air quality with natural ventilation

One part of the project was to determine IAQ with natural ventilation. Therefore, we turned the ventilation systems off from time to time in some of the classrooms and instructed the teachers to vent as usual. Open windows and doors were detected by magnetic contacts. Figure 2 shows measured CO_2-concentration and occupancy on a school day in one of the classrooms.

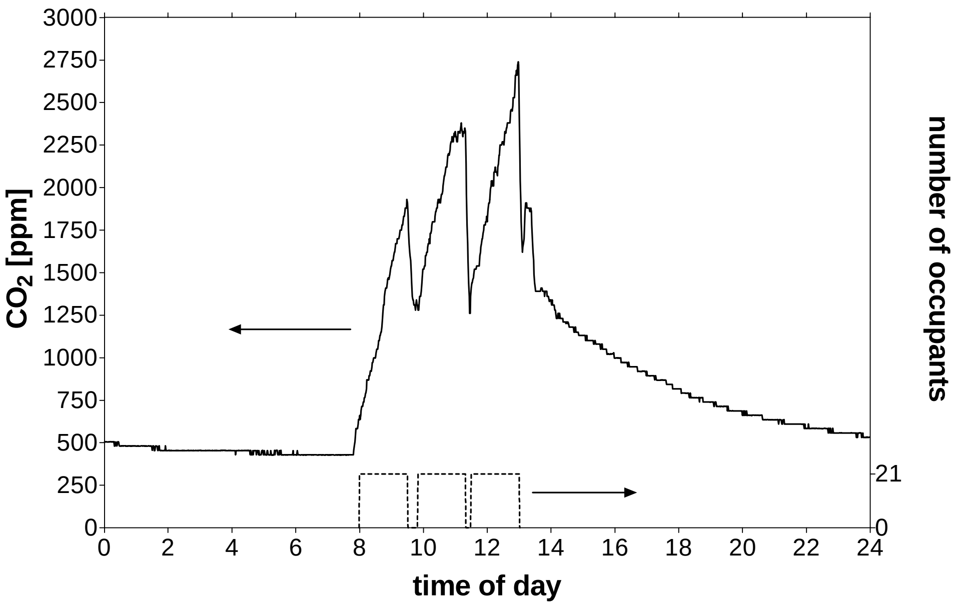

Figure 2: Amount of CO_2 and number of occupants in a naturally ventilated classroom during teaching. The outside air temperature varied between 0 °C and 5 °C (data from December 8th 1999).

The amount of CO_2 continually started to increase at 8 am. This increase was interrupted during the breaks when the door was opened and the children left the room. CO_2-concentration dropped during this time due to enhanced air exchange through the door and a lack of emission sources. Afterwards, CO_2 started to increase again and achieved even higher values at the end of the following lessons. This led to maximal peak CO_2-concentrations of 2750 ppm for. The windows were closed all the day, which was a common situation for most of the classrooms, at least during the winter months. The mean daily window opening times of the classrooms are shown in Table 2.

Table 2: Daily window opening times (mean values for an 8 week period) and number of occupants of the four classrooms. Teaching is done 6 hours per day with each teacher having it's own classroom.

	Room 1	Room 2	Room 3	Room 4
Class size	21	17-21	18-23	25
Duration of window opening [min/day]	32	35	9	2

According to Table 2, the ventilation duration varies strongly with the responsible teacher. Two of the teachers (rooms 3 and 4) kept the windows closed almost all the time. The others opened the windows for about half an hour per day, which approximately corresponds to the total break duration. However, closer examination shows no correlation between time of window opening and breaks. Windows sometimes were opened for several hours or for the whole day, whereas they weren't opened at all on many other days. A result of the first case was acceptable air quality but a high heating demand. The second case led to very high CO_2-concentrations. Figure 3 summarises the results of the CO_2-measurements.

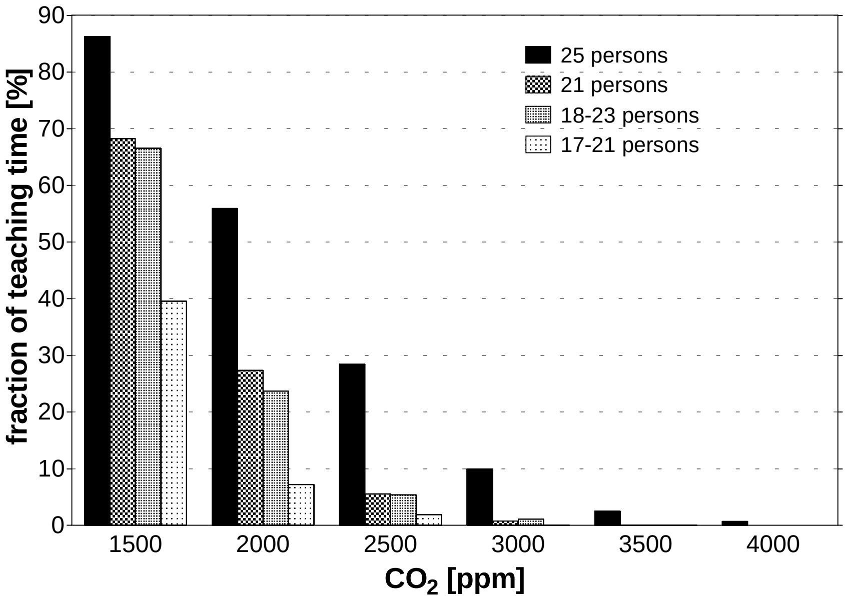

Figure 3: Fraction of teaching time during which measured CO_2-concentration in naturally ventilated classrooms exceeded abscissa values (measuring period was 8 weeks).

As Figure 3 indicates, measured CO_2-values exceeded the hygienic limit of 1500 ppm [4] very often (40 - 86%, dependent on class size). Significantly high CO_2-concentrations above 3000 ppm were recorded for class sizes of 25. The correlation between class size and CO_2-concentration was reinforced due to the fact, that the room with the greatest number of occupants was ventilated most seldom.

With respect to the obtained CO_2-values, natural ventilation via window opening must considered an insufficient strategy to achieve adequate IAQ in classrooms.

4 Demand controlled ventilation

4.1 Indoor air quality

Each of the mechanically vented classrooms was monitored for several weeks. A continuous basic air flow rate of 60 m^3/h was maintained. Additionally, we used CO_2-concentration as control parameter for the ventilation systems. All windows were kept closed during this time to eliminate any interference. The amount of CO_2 as well as the air flow rate were recorded. Figure 4 shows measured CO_2-concentration and air flow rate for the same classroom than in Figure 2. The two graphs are comparable since the measurements were performed for identical occupancy and during similar weather conditions.

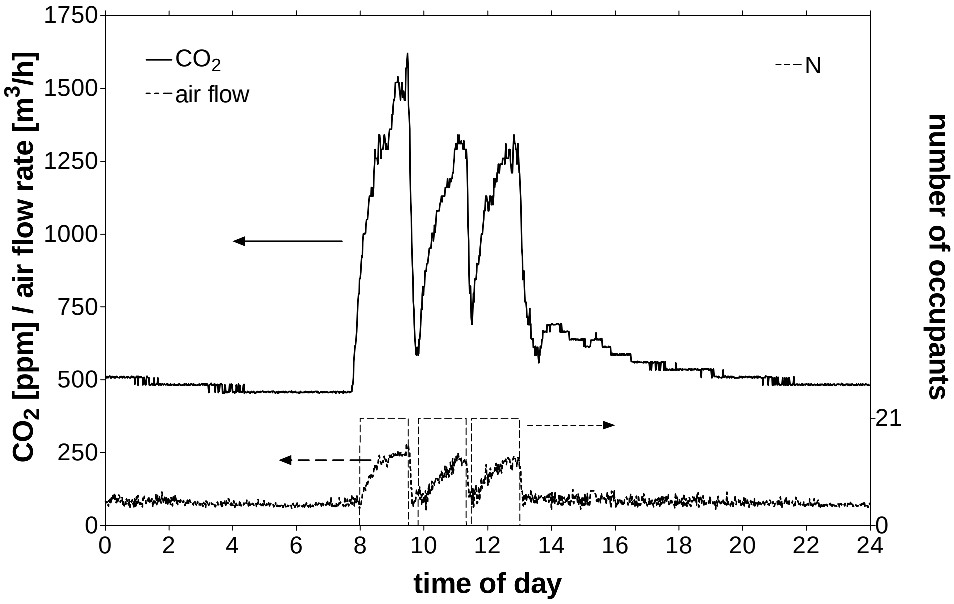

Figure 4: CO_2-concentration, air flow rate and number of occupants in a mechanically ventilated classroom. The outside air temperature varied between 0 °C and 5 °C (data from December 1st 1999).

Compared to natural ventilation measurements (Figure 2), the mechanical ventilation system significantly reduced CO_2-concentration. Maximal peak values of 1500 ppm were exceeded only once for a short time. Figure 5 gives a summary of the CO_2-measurements in the mechanically ventilated classrooms.

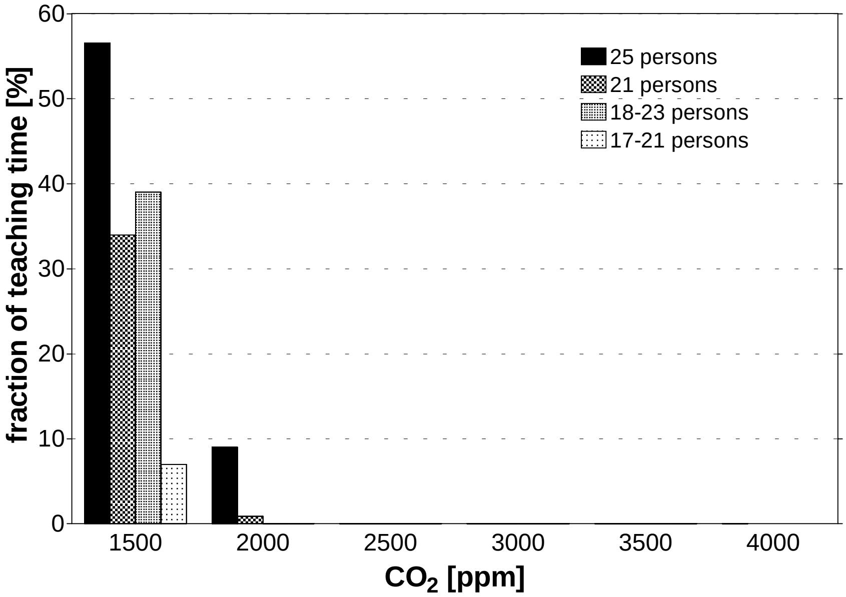

Figure 5: Fraction of teaching time during which measured CO_2-concentration in mechanically ventilated classrooms exceeded abscissa values (measuring period was 4 weeks).

The CO_2-values depicted in Figure 5 give evidence for a considerable improvement of IAQ compared to the results obtained for natural ventilation (Figure 3). Maximal peak values could be reduced from 4000 ppm to slightly above 2000 ppm. Nevertheless, it must be stated that the ventilation system was designed too small to keep CO_2-concentrations always within hygienic limits, even in the rooms with smaller class sizes.

4.2 Ventilation heat losses and electrical power consumption

For an assumption of ventilation heat losses, an exponential decay curve fit of CO_2-concentration was used to calculate infiltration rates. We found air exchange rates due to leakage in the range of 0.2 h^{-1} for all of the rooms. With the recorded air flow rates, we calculated the weekly mean air exchange rates with mechanical ventilation. In case of natural ventilation, we used a leakage air exchange rate of 0.2 h^{-1} which was set to 1 h^{-1} during times of opened windows. The results are shown in Table 3.

Table 3: Weekly mean air exchange rates of the classrooms due to natural and mechanical ventilation.

	Room 1: n [h^{-1}]	Room 2: n [h^{-1}]	Room 3: n [h^{-1}]	Room 4: n [h^{-1}]
Natural ventilation	0.22	0.23	0.20	0.21
Mechanical ventilation	0.38	0.38	0.36	0.41

In case of natural ventilation, the mean air exchange rates barely exceed infiltration rates. This is due to the short duration of window opening described in section 3. The mean values of the air exchange rates with mechanical ventilation are in the range of 0.4 h^{-1}. Therefore, we expected heat consumption in the mechanically ventilated rooms to be about 50 kWh per week higher than in rooms with natural ventilation.

To confirm this, the heating power of the radiators was measured by use of electronic heating cost distributors. Their signals corresponded to the sum of ventilation and transmission heat losses and had to be adjusted for solar and internal heat gains. Additionally, the outdoor air temperature had to be taken into account. The so corrected heat consumption was within a range of 600 to 1100 kWh per week and room. This implies a contribution of ventilation heat losses of only about 5 to 20% which is typical for poorly insulated buildings. Table 4 compares the mean weekly heat consumption of the naturally and mechanically ventilated classrooms.

Table 4: Mean weekly heat consumption of the four classrooms with respect to ventilation operation.

	Room 1: Q [kWh/week]	Room 2: Q [kWh/week]	Room 3: Q [kWh/week]	Room 4: Q [kWh/week]
Natural ventilation	874	900	793	788
Mechanical ventilation	908	970	760	722

According to the results shown in Table 4, there's no significant increase in heat consumption for rooms with mechanical ventilation. A reasonable explanation is the small contribution of ventilation heat losses to total heat consumption. Uncertainties arise due to difficulties in obtaining exact values for solar and internal heat gains.
The electrical power consumption for each of the ventilation systems was 2.0 - 2.5 kWh per week. It was calculated from the recorded control voltages of the exhaust fans and the rated fan powers. Assuming a school year of 38 weeks, the ventilation systems will require 76 – 95 kWh of electrical energy per year and room.

5 Hygiene measurements

The school building consists of fair-faced brickwork without insulation ($U \approx 1.6\ W/m^2K$). An inspection of the classrooms revealed severe mould problems, especially on window embrasures and corners of external walls. Surface samples yielded high concentrations of Cladosporium as well as some Penicillium, Aspergillus and Ulocladium. Aspergillus might be related to buildings with moisture problems, since it was found only within such buildings in a comparison study [5]. The same study indicates, that the amount of viable airborne fungi in mould contaminated classrooms seems to increase during lessons due to activity of the children. To verify this, we measured the concentration of mould spores and bacteria in the classroom air via culture dishes. All dishes were arranged in desk height and exposed to room air for 1 hour. This was done before teaching as well as during the first and second lessons. Figure 6 shows the resulting fungi and bacteria concentrations in one of the classrooms.

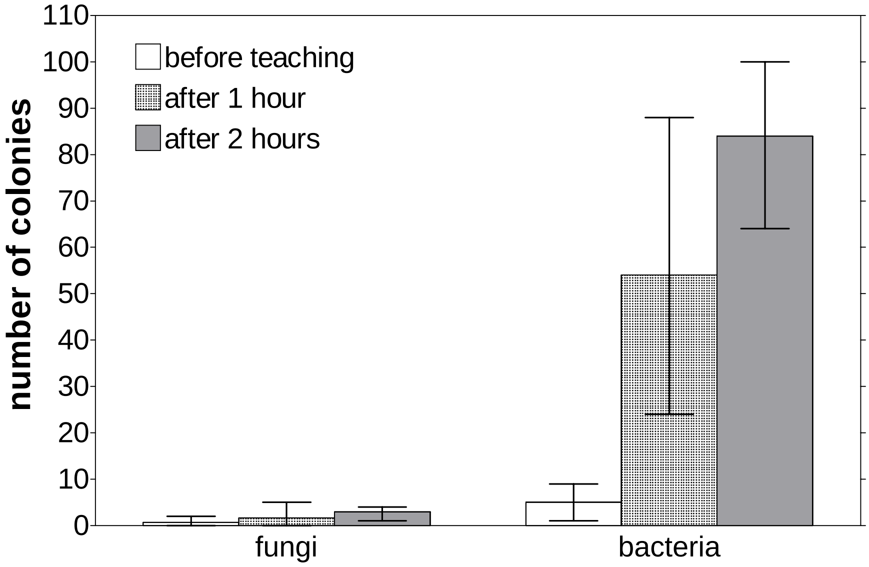

Figure 6: Mean values of airborne viable fungi and bacteria concentrations in one of the mould infested classrooms (25 people). The "error bars" represent maximum and minimum values of measured colonies (data from March 2nd 1999).

The detected concentrations of both airborne fungi and bacteria were very low in the empty room. In contrary to [5], we found no significant increase in airborne fungi concentration due to the presence of children. However, the children caused an increase in bacteria concentration. An analysis of detected bacteria revealed no abnormal species. After these preliminary studies, the mould infested areas were removed.

Additional measurements were performed to investigate the influence of the ventilation systems on hygienic conditions. The bacteria concentrations in a naturally and a mechanically ventilated classroom are shown in Figure 7.

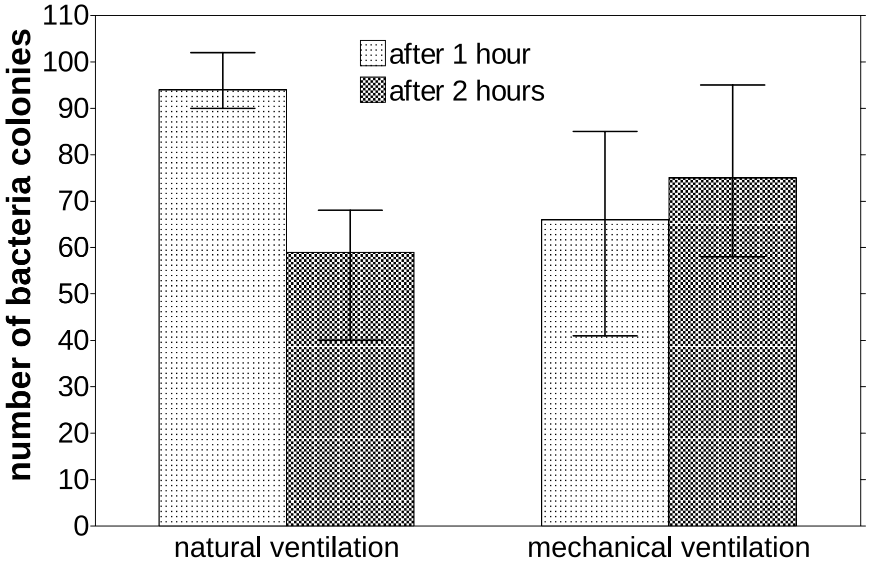

Figure 7: Mean values of airborne viable bacteria concentrations in two classrooms. The windows in the naturally ventilated classroom (25 people) were closed during the measurements. The other classroom (21 people) was ventilated mechanically. The "error bars" represent maximum and minimum values of measured colonies (data from December 2nd 1999).

The bacteria concentrations in the naturally ventilated classroom did not differ significantly from that obtained in March 1999, thus confirming those results. Although the air exchange rate in the room with mechanical ventilation was about 5 times higher (1.0 h^{-1} compared to 0.2 h^{-1}), this had no influence on bacteria concentration. Control measurements of outdoor bacteria concentration revealed very low values. A contamination of the mechanically ventilated classroom due to outdoor air thus was impossible. Human beings emit a large amount of bacteria [6], so an air exchange rate of 1 h^{-1} may not be sufficient to reduce these bacteria concentrations. To investigate this further, an additional classroom was included in the next measurements. The classroom was naturally ventilated, but the windows were wide opened before teaching and between the two lessons to achieve high air exchange rates. The deposition time of the culture dishes was 30 minutes before teaching and 45 minutes each during the next two lessons. The results of the hygiene measurements are shown in Figure 8.

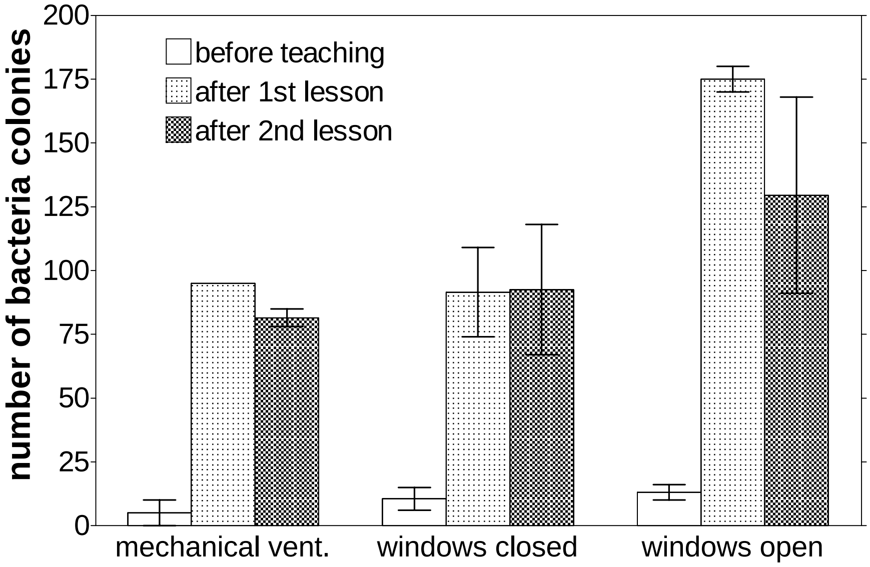

Figure 8: Mean values of airborne viable bacteria concentrations in three classrooms, two with natural and one with mechanical ventilation. The windows in one of the naturally ventilated classrooms (18 people) were closed during the measurements. In the second room (25 people), the windows were opened for 15 minutes before teaching and between the two lessons to increase air exchange rate. The "error bars" represent maximum and minimum values of measured colonies (data from March 30th 2000). In the mechanically ventilated room (17 people), only one culture dish could be evaluated after the first lesson.

In consistence to the measurements previously done, there was no significant difference in detected bacteria concentration between the mechanically ventilated and the naturally ventilated classroom with closed windows. The bacteria concentration in the naturally ventilated classroom with opened windows was higher. That may be due to the fact, that this classroom had the greatest number of occupants. However, there may be another explanation. Airborne bacteria usually sink to floor level, so only those swirling through the air, which in fact impose the greatest health risk on occupants, may be detected by culture dishes. The high air exchange rates due to wide opened windows may have led to air turbulence which increased the amount of bacteria in the air and thus resulted in higher detected bacteria concentrations. This corresponds to a study which found an increase in airborne germ concentration in surgery rooms in case of highly turbulent ventilation systems [7]. In this case, a strong argument in favour of controlled, laminar-flow ventilation would be given. Future measurements are planned to investigate this question.
Surface samples of the previously contaminated areas showed very low fungi concentrations comparable to that of noncontaminated areas. This indicates increased air exchange rates with lower humidity values in the mechanically ventilated classrooms.

6 Acceptance of the ventilation systems

The teachers were instructed to fill out a questionnaire to summarise their experiences with the ventilation systems. The answers show a slight improvement in perceived air quality due to the ventilation systems. There were absolutely no problems with respect to noise or draught. In this point all of the teachers answered solely positive. A similar result was obtained for acceptance of the ventilation systems. All teachers would prefer classrooms with mechanical ventilation systems instead of rooms vented by window opening. Furthermore, all of the teachers would support the installation of mechanical ventilation systems in other classrooms, not equipped with this technique.

7 Discussion

The hygienic limits for CO_2-concentration are often exceeded in naturally ventilated classrooms. Although open windows can result in large air flow rates, practice shows, that the windows were opened too seldom, especially in winter. The result is an increased concentration of air pollutants and bad odour, which may cause tiredness, lack of concentration or health problems, like allergic irritation [8], [9]. Mechanical ventilation systems can improve this situation. The amount of air pollutants and humidity loads can be reduced, which helps to eliminate mould problems. The effect of mechanical ventilation systems on airborne viable bacteria concentration has to be investigated further.
In Germany, main difficulties for a wide operation of mechanical ventilation systems in public buildings are the prevailing opinion that natural ventilation is sufficient and reservations that doubt a flawless system performance. Unfortunately, many realised projects confirm the legitimacy of the latter. In case of mechanical ventilation systems in residential buildings, there often are problems concerning draught, noise and controllability [10]. We could show with this study, that natural ventilation by window opening often is not sufficient to achieve acceptable IAQ and that the operation of cheap ventilation systems is possible without any of the aforementioned problems.

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