Effects of supply air temperature and pollutant location on concentration characteristics with a night-time ventilation in a school classroom

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Abstract. Night-time ventilation is used to remove indoor pollutants before the occupied periods. However, a lack of knowledge exists on how well a minimum level of ventilation can dilute pollutants during the night, and how a location of a polluting source and a supply air temperature affect the concentration levels with a typical mixing ventilation strategy. Therefore, the constant polluting source of 12 mg/h was defined on the floor (60 m^2), sidewall (17 m^2), and floor-corner (1 m^2) describing a low-polluting floor material of 0.2 mg/h,m^2 (EN 15251:2007). The objective of the study was to demonstrate a minimum night-time ventilation scenario of 0.15 L/s,m^2 with the isothermal supply air, underheated supply air (-4°C), and overheated supply air (4°C) compared to indoor air initial temperature. Furthermore, the temporal and spatial concentration characteristics were considered. The daytime ventilation was 3 L/s,m^2 with the underheated supply air temperature. Both the night and the day periods lasted 12 hours. The room air distribution was arranged by using 2 corridor wall supply air grilles and 4 exhaust air valves. However, only 1 grille and 2 valves were used at night. ANSYS CFX tools were used for numerical modelling. The RANS and URANS simulations were carried out with the implicit pressure-based multigrid coupled solver. The second-order discretization schemes were used in space and time and the SST-model was chosen to model turbulence with the automatic wall treatment. The convection-diffusion equation was used in scalar transportation. The measured data were used as boundary conditions and the computational grid adaptation was applied to improve accuracy. The results show that the underheated supply air provided the lowest concentration level in the occupied zone because the low-temperature supply air flowed down to the floor and dilute well the occupied zone. The overheated supply air, in turn, provided the largest concentration level in the occupied zone because the heated air was not mixed well in the room. The isothermal supply air provided a circulating airflow pattern increasing the concentrations beyond the supplied airflow region. The daytime ventilation decreased the cumulated night concentrations to one-tenth within an hour.

Keywords. night-ventilation, school, pollutants, CFD, IAQ.
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1. Introduction

Ventilation is an important matter in reducing pollutants from the indoor environment [1]. Generally, the main target is providing clean air for people and maintaining indoor air quality and thermal comfort. Therefore, the air distribution flows and their interactions with surroundings are important matters to investigate. Night-time ventilation is typically used to remove indoor pollutants before the occupied periods. Finnish building code instructs that the minimum ventilation is 0.15 L/s per floor square for the unoccupied hours of non-residential buildings. European Standard EN 15251:2007 [2] recommends 0.1-0.2 L/s per floor square for the unoccupied hours or 2 air volume changes before occupancy. However, a lack of knowledge exists on how well a minimum level of ventilation rate can dilute and remove the pollutants during the night, and how the location of a polluting source and the supply air temperature affect the concentration characteristics.

Earlier studies have found that the increased TVOC concentrations in the mornings in non-residential buildings may occur due to off-gassing of building materials because the ventilation is not used at night [3], [4]. Consequently, the objective of this study was to investigate the effects of minimum ventilation level on different classroom pollutant sources. The study demonstrates a minimum night-time ventilation scenario of 0.15 L/s,m^2 with the isothermal, underheated (-4°C) or overheated (4°C) supply air. The research question was how the night-time ventilation should be used with the minimum ventilation.

CFD-simulation is a common modelling method while investigating indoor airflows [5]-[8]. In many cases, the Newtonian viscous incompressible flow equations are discretized by a system of linear algebraic equations at discrete locations in space and time [9]. The boundary conditions are then implemented to define the desired airflow field, and the initial conditions are used for describing a beginning moment of time-dependent computation. A numerical solution of linear algebraic equations is generally obtained by conducting the iterative methods.

The Reynolds-averaged Navier–Stokes (RANS) modelling has been commonly used to simulate a time-averaged indoor airflow field. In RANS, the Reynolds-averaged momentum equations provide nonlinear stress terms that must be modelled, because each unknown variable needs an equation. Therefore e.g. many well-known two-equation eddy viscosity models have been developed, in which the turbulent viscosity is added to reduce the kinetic energy from the predicted flow field. The turbulence affects remarkably the indoor airflow field by enhancing the heat and mass transfer and by increasing the flow disturbances and losses in the air jets and mixing layers. This may typically mean that the predicted air jets become wider, and the mixing layers increase faster downstream than without using the turbulence models. However, this depends greatly on the initial air jet velocity levels and interacting buoyancy flows in the airflow field.

In this study, the airflow field of a school classroom was modelled by using CFD-simulations. Three constant and equal total emission sources were placed in the different locations in the classroom. In addition, different supply air temperature levels were examined. The novelty of the study is in the effects of night-time ventilation use on the pollutant concentration characteristics in indoor air before space usage.

The CFD model was based on the previously created CFD model that was validated by comparing the experiments in a laboratory test room [10], [11]. The computational grid and the computational models were updated to meet new test cases.

2. Methods

2.1 classroom

The simplified classroom is shown in Fig. 1. The classroom is 10 m long, 6 m wide and 3.3 m high. The height of the suspended ceiling at the corridor side-wall was 3 m. Furthermore, the outer side-wall had a window.

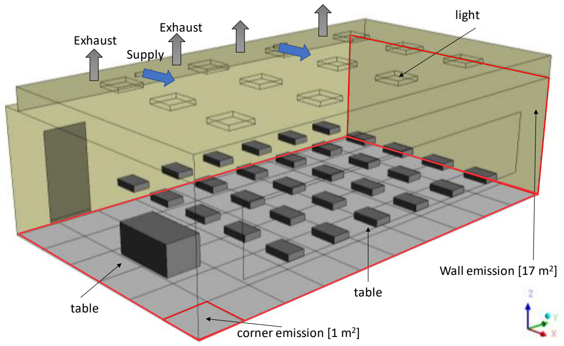

Fig. 1 The school classroom model.

2.2 pollutant sources

The three equal emission sources of 12 mg/h were placed to the different locations in the classroom. Each source describes a low-polluting material installed on the entire floor with an emission flux of 0.2 mg/h,m^2 [2]. In this study, these equal total source rates were located on the floor (60 m^2), on the side-wall (16.8 m^2), and on the floor-corner (1 m^2) which can be seen in Fig. 1. Therefore, the emission flux was the largest in the floor-corner source and the smallest in the floor source.

2.3 CFD-simulations

ANSYS CFX tools [12] were used for numerical modeling. The RANS and URANS simulations were carried out with the implicit pressure-based multigrid coupled solver. The second-order discretization schemes were used in space and time and the SST-model [13] was chosen to model turbulence with the automatic wall treatment. The convection-diffusion equation was used in scalar transportation. The measured data were used as the boundary conditions and the computational grid adaptation was applied to improve accuracy. In this way, the computational grid was automatically refined in the mixing layers of high-velocity gradients. The indoor air was ideal gas and pollutants were modelled as scalars, because tiny particles were considered. RANS simulations were used mainly in pre-simulations to test air distribution and computational grid levels. URANS-simulations were performed in 12-hour simulations.

2.4 air distribution

The ventilation method was mixing ventilation (Fig. 2). The daytime ventilation airflow rate was 3 L/s, m^2 with the underheated supply (dT=-4°C). This corresponds to the ventilation level of 6 L/s per person. Furthermore, this means around 3 indoor air changes per hour. The supplied airflow jet from the wall-grille device was 15 degrees upwards attaching to the ceiling due to pressure losses on the surface layer. The velocity profile at the grille boundary was provided by the device manufacturer (Halton Oy) that was applied to the given ventilation airflow rate. The change in speed level due to simplification of the terminal device was corrected by using a momentum source in front of the device. The ventilation was started smoothly such that the nominal level was achieved after 40 seconds from the start. In addition, the correct mass flow rate levels of exhaust valves were verified during the simulation.

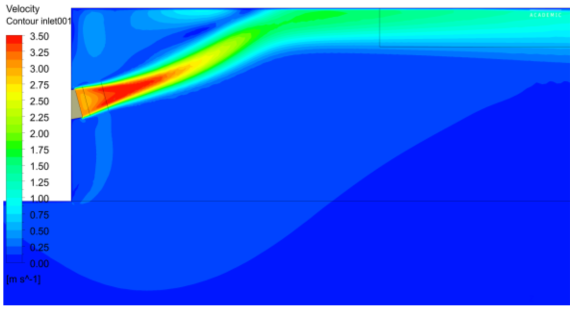

Fig. 2 The day-time ventilation supply air jet from the wall-grille device.

The day-time air distribution was arranged with 2 corridor wall-grilles and 4 exhaust valves. The night-time air distribution was arranged with 1 grille and 2 valves. Both the night and the day periods lasted 12 hours. The night-time ventilation was 0.15 L/s,m^2 with the isothermal, underheated (-4°C) or overheated (4°C) supply air. Fig. 3 shows the airflow streamlines from the supply air grille and the exhaust air valves. The difference arises from gravity.

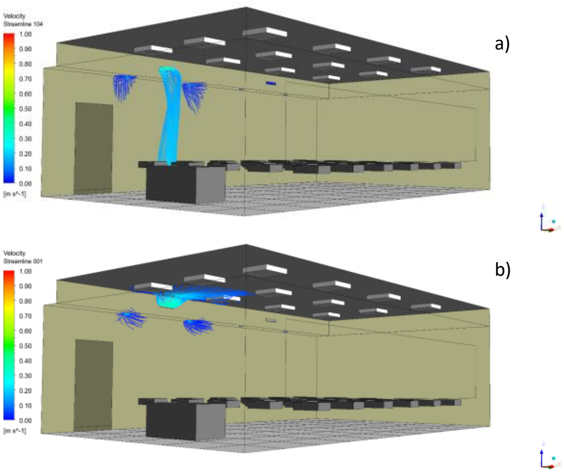

Fig. 3 The night-time supply air jet: a) underheated and b) overheated supply air.

2.5 Test cases

The test cases for the night-time ventilation were the isothermal, underheated (-4°C), and overheated (4°C) supply air. The night-time ventilation of 12 hours and the day-time ventilation of 12 hours were simulated by using URANS. In addition, the floor pollutant source, the wall pollutant source, and the corner pollutant source were compared. URANS time-step size was 1 s for the day-time ventilation and 10 s for the night-time ventilation. 3 internal iterations were used in each time-step. The wall boundary conditions were 22°C, window 21°C and the initial temperature of indoor air 21°C. The pollutant concentration characteristics of the school classroom was considered.

3. Results

3.1 concentration characteristics

Fig. 4 shows the predicted night-time increase of pollutant concentration level with the minimum ventilation of 0.15 L/s, m^2. In the graph, the concentration begins from the zero-concentration level and the pollutant source was the entire floor. Each curve represents a location in the middle of the room, inside the rectangle.

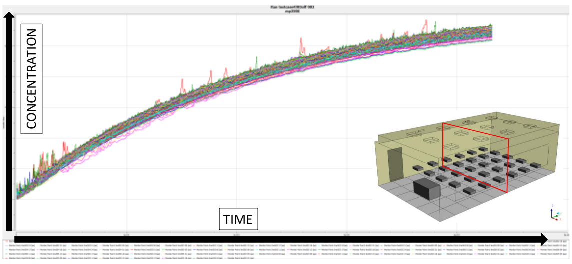

Fig. 4 Concentration characteristics in the middle of the room (marked with a rectangle). Transient simulation (URANS) for the 12 hour ventilation of 0,15 L/s,m^2. Floor emission 0.2 mg/h,m^2, dT_{supply}= -4°C.

In this case, the concentration was approaching stable conditions after 12 hours of minimum ventilation. The concentration characteristics are not linear but had a curved shape as approaching a balance with the ventilation. This describes the scenario where the pollutants from the floor material (12 mg/h) will increase the indoor air concentration during the night, and the minimum ventilation of 0.15 L/s,m^2 removes and dilutes the pollutant concentrations.

Generally, the spatial concentration differences between the different locations during the temporal development remained quite small with the mixing ventilation, which is seen as the distance between the curves on the vertical axis. When the day-ventilation is started, the concentration levels decrease rapidly. Fig. 5 shows the decay curve of concentration after the day-ventilation was started.

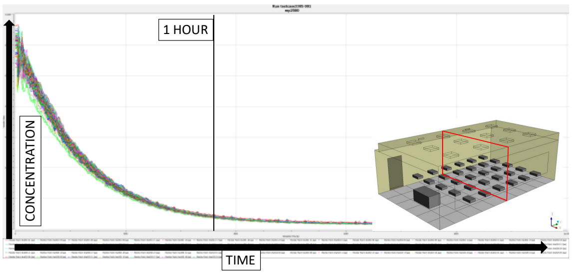

Fig. 5 Decay curve of floor emission of 0.2 mg/h, m^2. The day ventilation 3 L/s,m^2 was started up after 12 hour pollution.

The results show that the day-time ventilation decreased concentrations to 10% within an hour. Therefore, the results indicate that a 2-hour criterion for ventilation operation before the space usage is sufficient.

3.2 supply air temperature

Fig. 6 shows the dimensionless concentration level after 12 hours from the floor emission if the ventilation was not used at night. The predicted concentration level rises to about 5-7E-4 highlighting the regions near walls.

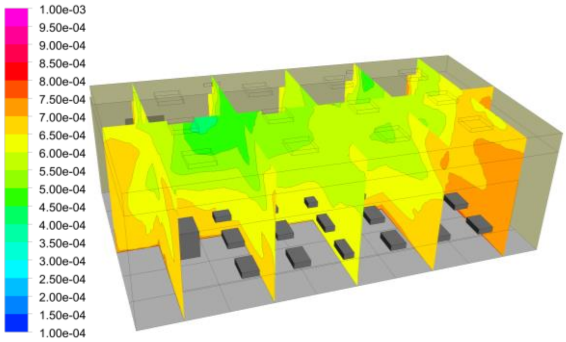

Fig. 6 The concentration characteristics without the ventilation from the floor emission 0.2 mg/h, m^2.

When the ventilation was used at night, the concentration levels decrease. The supply air temperature also affects the results because the gravity accelerates underheated supply air to the floor zone and the overheated supply air to the ceiling zone. Fig. 7 shows the corresponding concentration characteristics after 12 hours of minimum ventilation.

The results reveal that the underheated supply air flows on the floor by diluting the concentrations in the occupied zone. Consequently, the low-temperature supply air provided a rather well-mixed concentration field in the classroom.

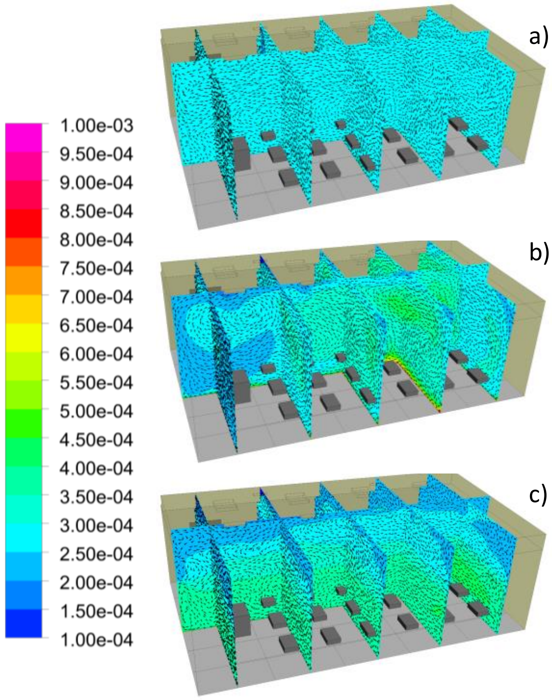

Fig. 7 The concentration characteristics with the floor emission after 12 hours of minimum night-time ventilation: a) the underheated supply air, b) the isothermal supply air and c) the overheated supply air.

The concentration range was larger with the isothermal supply air. The increased concentration levels were obtained beyond the supply airflow region, on the other side of the room. However, near the supply airflow, the concentration was at a low level. This is because the isothermal supply caused a rotating airflow pattern in the cross-section of the room, from the supply air device to the opposite wall side, affecting the concentration levels in this side of the room.

However, the highest concentration levels in the occupied zone were achieved with the overheated supply air because the warm air flows up to the ceiling zone and does not mix well with the indoor air. Consequently, the largest concentration range was achieved with the overheated supply air, while the smallest one was obtained with the underheated supply air.

3.3 location of pollutant source

Fig. 8 shows the pollutant concentration characteristics from the floor emission after the 12 hours of minimum night-time ventilation. The figure shows the volumes where the dimensionless concentration level was greater than 3E-4. The volumes show conveniently the differences between each test case.

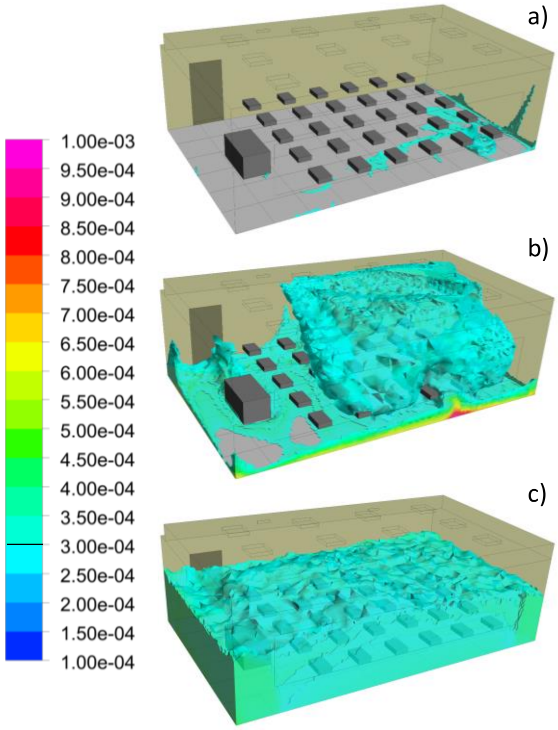

Fig. 8 The pollutant concentration (above 3E-4) with the floor emission after the 12 hours of minimum night-time ventilation: a) the underheated supply air, b) the isothermal supply air and c) the overheated supply air.

The results show that the underheated supply air provided the lowest concentration levels to the indoor air whereas the largest concentration levels occurred with the overheated supply air that was emphasizing the corners.

Fig. 9 shows the concentration characteristics from the wall emission. At the wall pollutant source (16.8 m^2), the underheated supply air increased the pollutant concentrations in the ceiling zone, while with the overheated supply air, the concentrations in the occupied zone increased. With the isothermal supply air, the increased concentration levels were more equally created beyond the supply airflow region, on the other side of the room.

The results reveal that the underheated supply is a reasonable choice when limiting the night-time concentration levels in the occupied zone before the day-ventilation is started.

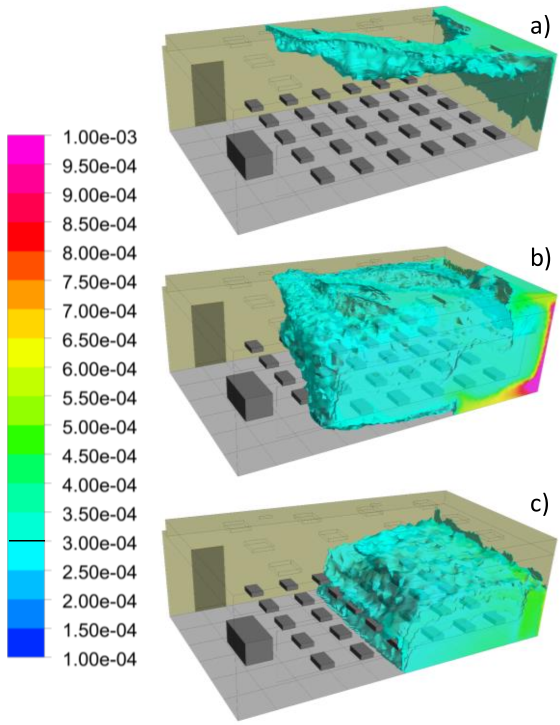

Fig. 9 The pollutant concentration (above 3E-4) with the wall-emission after the 12 hours of minimum night-time ventilation: a) the underheated supply air, b) the isothermal supply air and c) the overheated supply air.

Fig. 10 shows the concentration characteristics from the floor corner emission. With the underheated supply air, the high concentration levels existed near the corner and in the roof zone towards the supply airflow device. With the isothermal supply air, the increased concentration area became narrower than in the case of wall pollution source. With the overheated supply air, the increased concentration region occurred in the source corner side of the room. The concentration gradients increased greater towards the source than in the case of the wall pollutant source or the floor pollutant source.

The results indicate that the smallest concentration field was reached by using the underheated supply air due to better mixing of indoor air, while the concentration range increased with the isothermal and the overheated supply air. With the corner source, the isothermal supply air provided the largest low concentration region in the backside of the room. This was because the supply air was distributed from the pollutant corner side, and therefore, preventing the pollutants to spread so much to the other side of the room. By using the overheated supply air, the corresponding low concentration area existed in the roof zone.

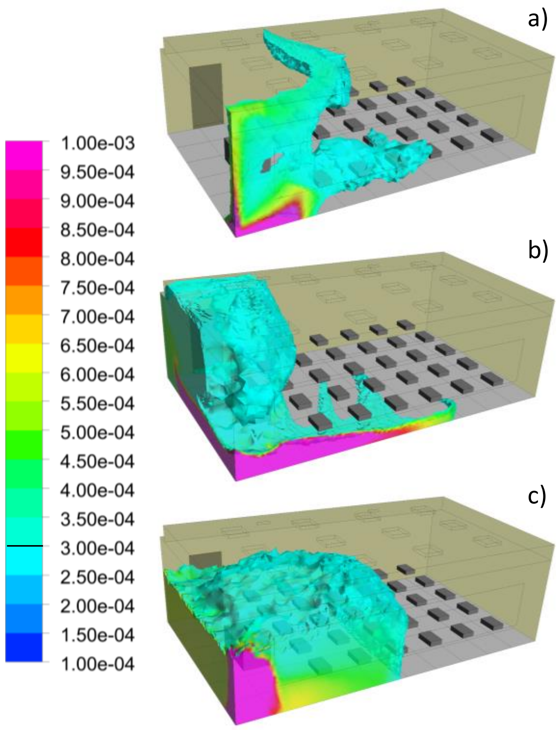

Fig. 10 The pollutant concentration (above 3E-4) with the floor-corner emission after the 12 hours of minimum night-time ventilation: a) the underheated supply air, b) the isothermal supply air and c) the overheated supply air.

The results show that the location of the pollutant source and its surface area affect the pollutant concentration characteristics. All the sources had the same emission rate in the room [mg/s], and therefore, the emission flux was the greatest in the floor corner ($1m^2$) and the lowest in the floor source ($60m^2$) [$mg/s, m^2$]. It follows that the highest concentration gradients exist near the smallest pollutant source and the smallest gradients near the largest pollutant sources due to those flux differences.

4. Discussion

Night-time ventilation is typically used to increase indoor air quality before space usage in public buildings. The study investigated the effects of supply air temperature and location of pollutant sources on the concentration characteristics of the school classroom by using the minimum level of night-time ventilation. Generally, the minimum level means the low ventilation airflows, and as a consequence, the supplied air jets are not behaving similarly than that of the day-time ventilation ones. Furthermore, the results showed clearly that the supply air temperature matters because the buoyancy forces accelerate the underheated supply air to the floor level and the overheated supply air to the ceiling zone. The overall conclusion is that the night-time ventilation may fasten a threshold time before the space usage in the mornings. In addition, night-time ventilation should be used with low supply air temperature levels. However, these results support the general 2-hour ventilation criterion before space use.

CFD-simulations showed that although the airflow rate is low, the night-time ventilation has an effect on the indoor airflow field. The underheated supply airflows dilute and mix with the surrounding air by decreasing the pollutant concentrations in the occupied zone. Consequently, the concentration levels were lower than that of the isothermal supply airflow or the overheated supply airflow. However, the isothermal supply airflow may prevent the pollutants to spread to the other side of the room. This means that even a low airflow may affect the pollutant dispersion in the room. Furthermore, it shows clearly that air distribution matters.

The different locations of pollutant source provided the different concentration characteristics in indoor air. The large floor emission with the lowest emission flux generated the lowest concentration gradients in the occupied zone whereas the smallest corner source with the highest emission flux generated the largest concentration gradients in the occupied zone, especially towards the source. Generally, the location of emission sources had negligible effects on the occupied zone when the low supply air temperature was used, because the indoor air was well-mixed in predictions.

5. Conclusions

The results indicate that the 2-hour criterion of ventilation is sufficient before the space usage. In predictions, the daytime ventilation reduced the pollutant concentrations to one-tenth within an hour.

The underheated supply air provided the lowest concentration levels in the occupied zone because the supplied air flowed down to the floor and diluted and mixed the indoor air in the occupied zone. Therefore, the night-time ventilation should be used with the low supply air temperature.

The overheated supply air was not mixed in the classroom, because the supplied air flowed to the ceiling zone. Therefore, the concentration levels were greatest in the occupied zone with the overheated supply air.

The isothermal supply air provided a circulating airflow pattern that was increasing the concentrations beyond the supplied airflow region.

The location of emission sources had negligible effects on the occupied zone when the low supply air temperature was used.

The spatial concentration differences between the different locations remained quite small with the mixing ventilation during the temporal development.

6. Acknowledgement

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7. Data access statement

The datasets generated during and/or analysed during the current study are not publicly available because the data are very case-specific and their applicability in other studies is limited, but the authors will make every reasonable effort to publish them in near future.

8. References

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