Healthy Buildings 2017 Europe
July 2-5, 2017, Lublin, Poland

Paper ID 0159 ISBN: 978-83-7947-232-1

Full-scale performance assessment of an innovative climate system for a classroom environment.

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SUMMARY

The indoor environmental quality (IEQ) of buildings affects health, productivity and well-being of its occupants. Simultaneously, energy consumption remains an issue of concern. IEQ in school buildings is critical, due to the high occupant density and influence of IEQ on student academic performance. In this research, the performance of an innovative system, combining ventilation and floor cooling/heating, is investigated through full-scale measurements in a mock-up and in a real classroom. Ventilation efficiency is assessed using the step-down tracer gas method. Thermal comfort focuses on local (non-uniform) thermal discomfort as this is most critical in a densely populated classroom. With increasing flow rates, the ventilation efficiency assessment shows a transition from displacement ventilation to mixing ventilation, and therefore reduced efficiency. Additionally, high flow rates can cause draught problems near supply grilles.

KEYWORDS

Indoor environmental quality, school, ventilation efficiency, local thermal discomfort.

1 INTRODUCTION

Indoor environmental quality (IEQ) of buildings affects health, productivity and well-being of its occupants (Heinzerling et al., 2013). Providing suitable IEQ in school buildings is critical due to the high occupancy density and influence of IEQ on the academic performance of students (Zomorodian et al., 2016). Deficient IEQ can cause absence from schools (Turunen et al., 2014), along with respiratory illness, allergies, asthma symptoms and sick building syndrome, all of which negatively affect occupant performance (Fisk, 2000). However, indoor air contaminants level and temperature are heavily influenced by the level of occupancy and activity rate (Madureira et al., 2016). At the same, time energy consumption of buildings remains an issue of concern, lower energy consumption being desired for environmental and economic reasons (Vringer et al., 2014).

Building codes and guidelines are in place to ensure a desired IEQ and efficient energy usage in (school) buildings. Stringent prescriptive requirements limit options for the introduction of innovative climate systems. The system under investigation in this research combines ventilation and floor cooling/heating (Figure 1). The principle assumes that the air, both for heating and cooling, is provided into the room at a lower temperature than the room air temperature with the intention to arrive at a condition similar to displacement ventilation. This is a more efficient type of ventilation than mixing ventilation. It therefore would allow for more lenient requirements on the air flow rates applied.

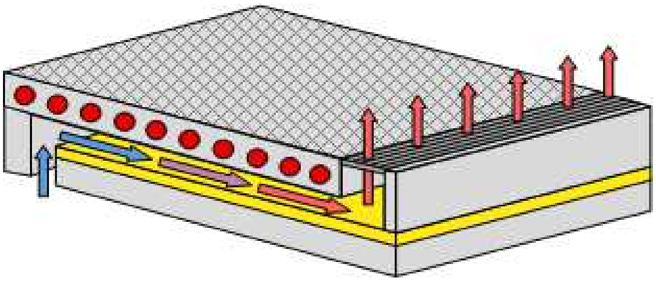

Figure 1. Schematic image of the ventilation air flow passing under the radiant floor.

This paper wants to answer the research questions regarding the system performance and which performance assessment approach would be suitable in this case. The performance assessment focusses on the physical performance and addresses common existing issues in school buildings: indoor air quality and thermal comfort (Bakó-Biró et al., 2012).

2 MATERIALS/METHODS

The performance of the system is investigated through full-scale measurements in a mock-up (Figure 2) and in a real classroom.

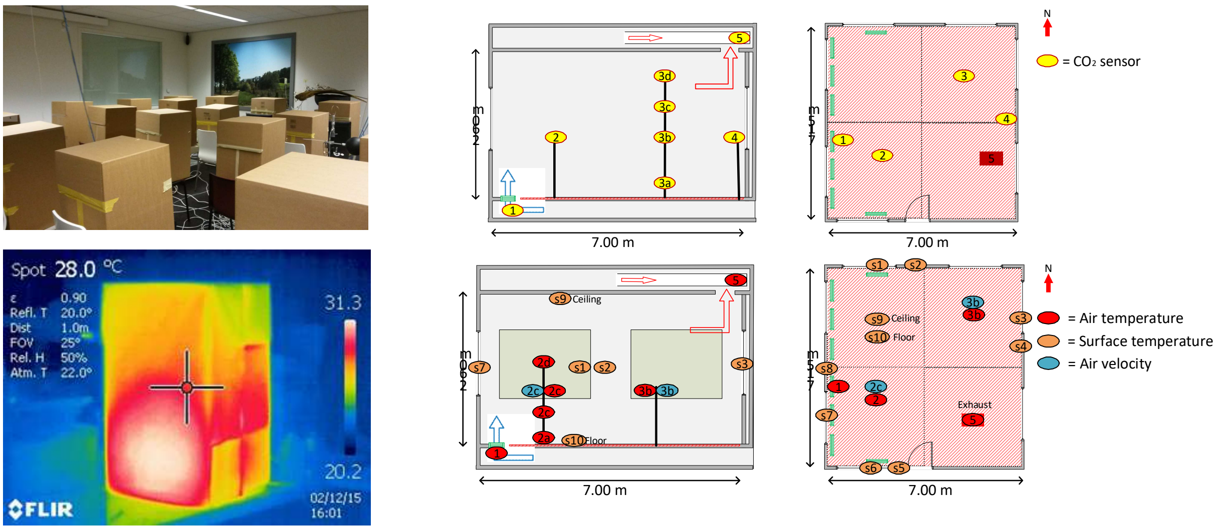

Figure 2. Photo of the full scale mock-up classroom (top-left), with heated boxes representing pupils (low-left) and measurement positions (right).

Ventilation efficiency and thermal comfort have been selected as performance indicators for the assessment. Ventilation efficiency is defined as the Air Change Efficiency (ACE). The ACE is the ratio between the minimum air replacement time and the actual mean air replacement time (Mundt et al., 2011). The minimal air replacement time is the ratio between the room volume and the total ventilation supply flow rate. To assess the actual mean air replacement time, the step-down tracer gas method is applied (Mundt et al., 2011) with CO_2 as the tracer gas. Though in the set-up the local air change index was determined at several positions, the actual mean air replacement time is determined from the three positions at the breathing height of a seated person (h=1.10 m). During each decay measurement (local) thermal comfort indicators were measured: the Predicted Mean Vote (PMV) (Fanger, 1970), the vertical air temperature gradient and the draught rate (NEN-EN-ISO 7730:2005). Vertical temperature gradient and draught rate are potential local thermal discomfort indicators related to (displacement) ventilation systems (Skistad, 2002). As the mock-up was placed in an unheated hall and measurements took place during winter 2015-2016, absolute thermal conditions may not always have been favourable. In a realistic situation, system sizing can be assumed such that thermal comfort requirements set in standards and guidelines are adhered to. System performance is based on temperature differences and therefore not assumed to be affected by absolute conditions. Draught rating would be an exception to this assumption.

The HVAC system in the mock-up classroom was tested under several settings. Ventilation supply flow rate per grille was varied between 45-100 m^3/h and the ventilation supply air temperature was varied between 9-21 °C. Ventilation air was supplied via 8 supply grilles in the floor (Figure 2 right; green rectangles). Ventilation efficiency and thermal comfort is influenced by the internal load in the room (i.e. the pupils). Heat load from 30 occupants is simulated by 30 cardboard boxes with a surface area of 1.44 m^2 each and a heat source of 84 W per box, similar to a young student with a sedentary activity (Figure 2). The number of cardboard boxes was varied as well, but most measurements involved all the boxes. This resulted in 13 different measurement scenarios in total. The scenarios where realistic with respect to combination of heating loads and set-points, though interest was in scenarios that required lower flow rates than guidelines would prescribe. Six of these measurement scenarios were repeated to determine the sensitivity of the measurement outcomes. Difference in ACE was lower than 12% for these cases and in line with accuracy found in literature (Sandberg, 1981; Amai and Novoselec, 2011). Four additional measurements were performed while fans induced higher air velocity, causing mixing. These measurements are used to compare the measured ventilation efficiency of the system with the ventilation efficiency of a mixing ventilation system. Finally, some measurements were performed with a continuous CO_2-source where CO_2 was inserted near the breathing height of the pupil (30 positions in total; 20 L/h.person). Data analysis was performed with Excel and Matlab.

Additional measurements were performed in a real classroom (floor area of 60 m^2), with the system installed and seven supply grilles in the floor, close to the facade. The room height varied between 2.8 m to 3.5 m. Three step-down tracer gas measurements were performed in the classroom. Thermal comfort conditions were measured alongside. The same heat emitting cardboard boxes were placed on the chairs of the 24 pupils and one teacher. The radiant floor was cooling during these measurements. The ventilation rate could not be changed manually between measurements. The supply flow rate during the first measurement was 73 m^3/h per supply grille. After maintenance, the other two measurements had a supply flow rate of 84 m^3/h per supply grille.

3 RESULTS

Ventilation efficiency

The measured ACE values as function of the air flow rate per grille are presented in Figure 3. The stripped line marks the ACE value of 50%, indicating mixing. ACE values higher than 55% assume displacement ventilation, thus more efficient ventilation. ACE values lower than 45% indicate slight short circuiting of the ventilation air, thus inefficient ventilation. It is important to repeat that the ACE values have been obtained from the average of the measurement positions at 1.1 m height.

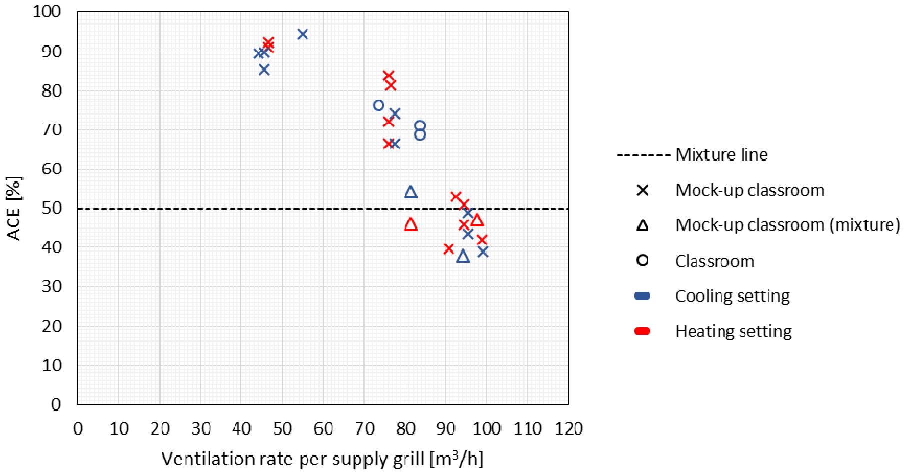

Figure 3. Air change efficiency based on the age of air measured at three positions, at 1.1 m height, in the room. Results from both the mock-up and the real classroom are included.

Local thermal comfort

Measured draught rate, as function of the air flow rate per ventilation supply grille, and the maximal vertical temperature difference, as function of the ACE, are presented in Figure 4. Larger vertical temperature differences are likely to occur with displacement ventilation (Skistad, 2002). The maximal temperature difference that is allowed according to the comfort classes (RVO, 2016) is indicated with horizontal dotted lines.

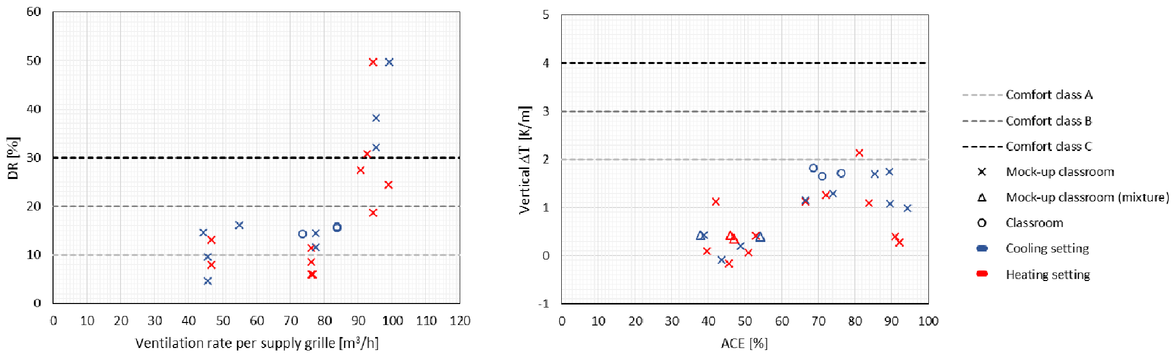

Figure 4. Draught rate as function of the supply flow rate per supply grille (left). Maximal vertical temperature difference as function of the ACE (right). Both graphs present results for the mock-up and the real classroom.

Continuous measurements

Results for the continuous CO_2-measurements are shown as function of time in Figure 5. Results for the original case and the mixing case are shown.

4 DISCUSSION

The ventilation efficiency (Figure 3) shows a transition from displacement ventilation to mixing ventilation, and therefore a reduced efficiency, with increasing supply flow rates.

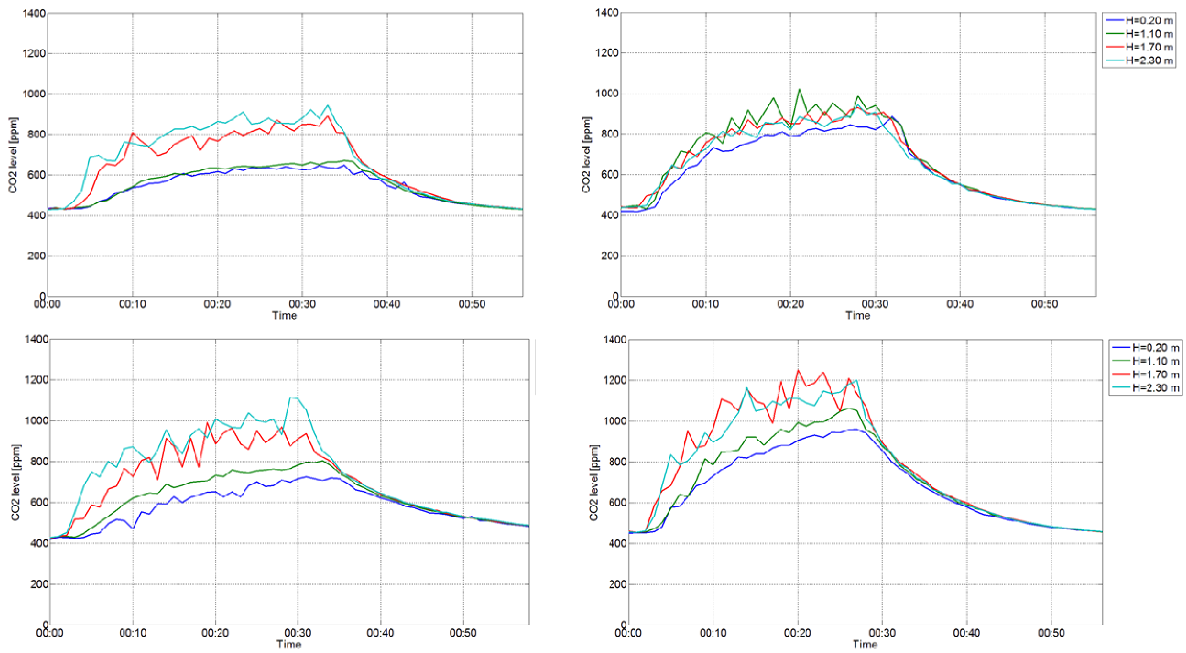

Figure 5. Continuous CO_2 measurements (mock-up; Top graphs at ~95 m^3/h.grille, Bottom graphs at ~80 m^3/h.grille; Left graphs for original system, Right graphs for mixing situation).

The measurements indicate a transition from displacement to mixing between 80 and 90 m^3/h (significant difference for ACE at supply grille flow rates <80 m^3/h and ACE at supply grille flow rates >90 m^3/h; Wilcoxon rank sum test, W_s=78, z=-3.68, p<0.001, r=-0.82). This would mean that higher flow rates do not always support improved air quality. The high flow rates are in line with the current building code requirements and guidelines. The outcomes assume that a minimum required air change rate may not be supportive in this case. A correction for the ventilation efficiency would be a favourable outcome.

The actual ACE values for an assumed displacement ventilation condition appear high. This results from the fact that only three positions in the room at 1.1 m have been used to assess the ACE. Two reasons were in place for that decision. Firstly, at this height, ventilation efficiency conditions are most important. Secondly, an inconsistency was noticed in the analysis of the data that did not clearly indicate a gradient over the height. Causes for that may relate to the position of the measurement equipment, relative to the supply and heat sources in the room. Furthermore, consistent application of the procedure (Mundt et al. 2011) was not straightforward. Nevertheless, the presence of a vertical temperature gradient (Figure 4 [right]; significant difference in ΔT for ACE<60% and ACE>60%; Wilcoxon rank sum test, W_s=49, z=-2.67, p<0.01, r=-0.59) and the outcomes for the continuous measurements support the conclusion of a transition in flow pattern for this case, while questioning the absolute value of the ACE.

From the results and expected flow patterns, local thermal discomfort for the case could be expected for a cooling situation and at higher supply flow rates. For the investigated conditions, both performance indicators (vertical temperature gradient and draught) provided minimal issues. Higher ventilation rates reduce the vertical temperature gradient (Chen et al., 1999). However at the investigated lower flow rates (high ACE) the temperature gradient remains <3 K/m. Potential draught risk was identified at higher supply flow rates (>90 m^3/h.grille) and near the supply grilles. Higher flow rates are therefore not favourable for thermal comfort performance. Instead of focussing on the supply flow rate only, optimization of ventilation efficiency and local thermal comfort performance indicators would be beneficial. This could of course affect the design of the supply grille as well.

5 CONCLUSIONS

Prescription of minimum airflow rates for ventilation in school buildings may not result in optimal design outcomes and may overlook alternative solutions. As class rooms are complex environments, the assessment procedure should include the ventilation efficiency as a performance indicator for a fair optimization of the system design in class rooms.

The procedure developed allows assessment in the design and use phase. The technique would, however, gain further credibility by additional research into the analysis of the step-down tracer gas measurement.

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