Thermal Comfort and indoor air quality in Drøbak Montessori School – A case study of Norway's first plus-energy school

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ABSTRACT

Drøbak Montessori lower secondary school is Norway's first plus-energy school and also the first school built after the Norwegian Powerhouse-concept, www.powerhouse.no. This concept implies that the building shall produce more renewable energy during the lifetime of the building, than used for materials, production, operation, renovation and demolition.

To achieve the energy ambitions for the project there has been a high focus on obtaining an effective and low-pressure ventilation system. The chosen solution is a concept with relatively tall rooms with displacement ventilation that varies between fully mechanical and hybrid ventilation depending on the time of the year. The extract air is removed from the rooms by overflow to adjacent areas. During summer the exhaust air is directly let out through an opening in the top of the centrally placed atrium. In the heating periods the exhaust air is driven mechanically through the air handling unit for heat recovery.

The school has an all-air HVAC-system where all the heating and cooling demand for the building are covered by the ventilation system, no additional heating sources is installed in the building. Room heating only provided by ventilation is not something new, but is often combined with mixed-flow ventilation. At the Montessori school in Drøbak the heating with ventilation is combined with displacement ventilation. To avoid a short circuiting of the supplied fresh-air when the occupants are present, the air is supplied with a lower temperature than the surrounding air. During night time the system switches to heating mode when necessary, depending on recorded indoor and outdoor temperatures. When in heating mode, the supply air is recirculated and heated to a supply temperature higher than the surroundings. The supply air temperature depends on the outdoor temperature and the airflow is demand-controlled based on temperature and CO_2.

To ensure that the chosen solution provides a satisfactory thermal indoor climate and to provide input to the tuning and optimization of the control strategies, simulations with a two-zone model, advanced simulations in IDA-ICE, laboratory tests and field measurements has been performed.

This paper will present the analysis, results and conclusions from the above mentioned two-zone model compared to the results from the field test. The results from the advanced simulation in IDA-ICE and the laboratory tests will not be presented in this paper.

The results from the two-zone model and the field test show promising results when it comes to achieving thermal comfort by using displacement ventilation for heating. The results also shows good consistency between the 2-zone model and the measured data from the field test. This research will provide useful knowledge for future projects when it comes to minimizing the energy use, costs and complexity for HVAC-installations in buildings where displacement ventilation is suitable.

KEYWORDS

Displacement ventilation, 2-zone model, field test, ventilation heating

1 INTRODUCTION

Drøbak Montessori lower secondary school is a school with 60 students divided between 8th and 10th grade. There is a wish to include the 7th grade in the long term and thus become 80 students. The vision of the school is “learning through experience” which is emphasized through student activity and interdisciplinary. The area of the new school building is just below 900 m² heated area and is organized on one level with a lower floor under parts of the building where the terrain has a natural fall. The building has a compact rectangular shape oriented southeast-northeast. The building is intersected by an inclined slice “the solar slice”. The building is shown in figure 1.

Figure 1: Drøbak Montessori lower secondary school. Source: www.powerhouse.no

The vision of the school is to become “Norway’s most environmentally friendly school”. The school is the first new build to fulfill the requirements for the Norwegian Powerhouse-concept.

The heating and ventilation concept for the school where chosen because of limited financial resources, desire for a simple HVAC system and with the energy ambitions in mind.

2 METHODS

To validate the ventilation system, ensure that the chosen system provides satisfactory thermal indoor climate and provide input for optimization and tuning of the system a field test has been performed at the school. The results from the field test has been compared with simulations in a two-zone model.

The field test was carried out in a classroom located in the lower floor. The class room is shown in figure 2. During the occupied hours, from 7.30 AM to 4 PM, the ventilation system is operated in “normal modus” where the air flow rate is depending on the CO_2 and temperature in the actual room. The supply temperature during the occupied hours is depending on the outside temperature as showed in figure 3.

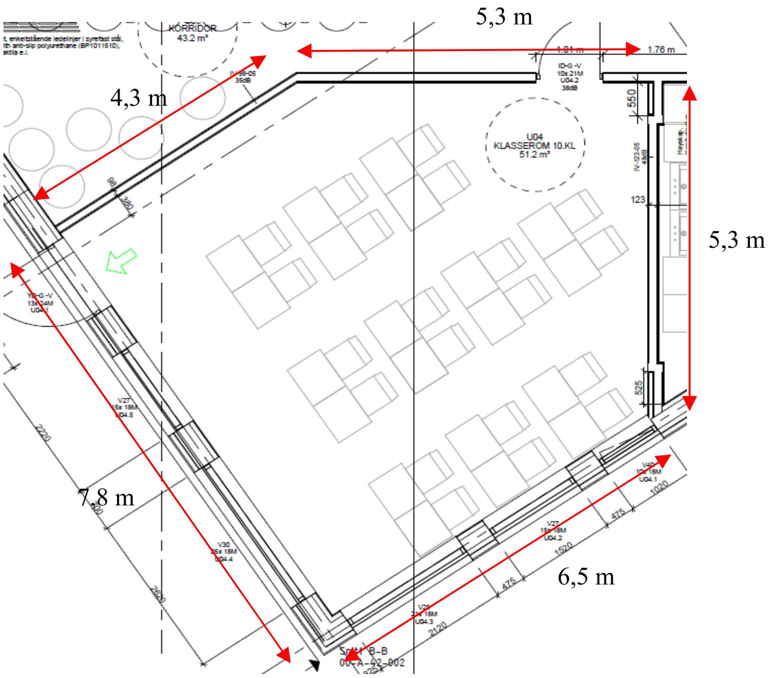

Figure 2: The class room used for the field experiment.

The school is well insulated and the thermal mass of the class room can be rated as medium, details given in table 1.

Table 1: Geometry and U-values for the classroom.

	Value
Heated floor area	51,2 m²
Internal height	3,0 m
Heated volume	153,6 m³
Area external walls	24,1 m²
Area internal walls	44,7 m²
Area windows	18,8 m²
U-value external walls	0,14 W/m²K
U-value windows	0,75 W/m²K
U-value floor*	0,10 W/m²K
Heat capacity walls	2,4 Wh/m²K
Heat capacity floor	63,0 Wh/m²K
Heat capacity ceiling	3,0 Wh/m²K

* See also section 2.2 for further details on floor heat loss.

Outside of occupied hours the ventilation system is switched into heating mode in the heating season and into cooling mode in the cooling season.

In heating mode the air flow rate is depending on the temperature in the actual room. When the measured internal temperature in the actual room reaches a lower temperature of 19 °C the heating of the room starts. In the heating mode the air flow rate for the room is set for the maximum calculated air flow rate for the room. When the room reaches its set point for heating, the air flow is reduced to a minimum, ensuring that the heating is applied to where it is needed. In the heating mode the supply temperature for the ventilation system is depending on the measured outdoor temperature as shown in figure 3.

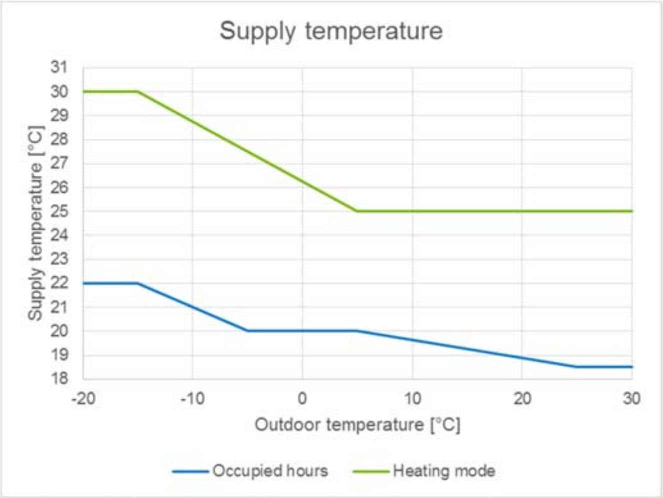

Figure 3: Supply temperature in occupied hours and for heating mode as a function of outdoor temperature.

2.1 Two-zone models

In displacement ventilated rooms, as schematically shown in figure 4, there will naturally be a lower clean and cool zone and a more polluted and warm upper zone. Based on this fact a two zone model for temperature stratification and contaminant stratification can be made. The thermal two-zone model used in this paper is based on a six node-two mass model, the major variables given in figure 4. The model can be reduced to two linear differential equation which can be solved analytically, giving the mass temperature, the surface temperature and room temperature in the two zones. Based on this temperature indices, temperature gradients, operative temperature in the occupation zone and more can be calculated. In a recent paper (Dokka, 2018) the model is described and validated against measured data with good results.

Similar for contaminant stratification a two zone model has been developed, also resulting in two coupled linear differential equations which can be solved analytically. This model can e.g. be used to calculate contaminant stratification (e.g. CO_2) and to calculated different ventilation efficiency indices. This model has also been compared to and validated against measured data with very good results (Dokka, 2017).

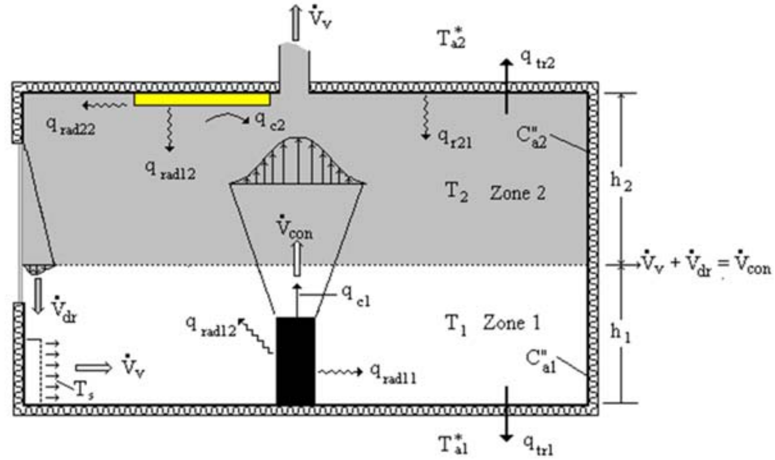

Figure 4: Schematics of the two zone thermal model.

2.2 Field experiments

The field experiments were conducted on February 8th, 2018. The field test consisted of measurements of dry bulb temperature, operative temperature, air velocities and CO_2-consentration. In this paper the focus will be on temperature and CO_2. The classroom was occupied with students and teachers during the experiment. The type and accuracy of the used sensors for measuring temperature and CO_2 concentration during the experiment are listed in table 2.

Table 2. Type and accuracy of sensors.

Sensor measuring	Type	Measuring	Range	Resolution	Accuracy
CO_2/temperature/ relative humidity	Extech SD800	Temperature	0,0 to 50,0 °C	0,1 °C	±0,8 °C
		CO2	≤ 1000 ppm	1 ppm	± 40 ppm
			> 1000 to ≤ 3000 ppm	1 ppm	± 5 % of reading
			> 3000 ppm	1 ppm	± 250 pp typical
Temperature/ relative humidity	HOBO UX100-011	Temperature	-20 °C to 70 °C	0,024 °C at 25 °C	± 0,21 °C from 0 °C to 50 °C

The measuring sensors where placed in two different locations mounted on wooden poles in 4 different heights as shown in figure 5.

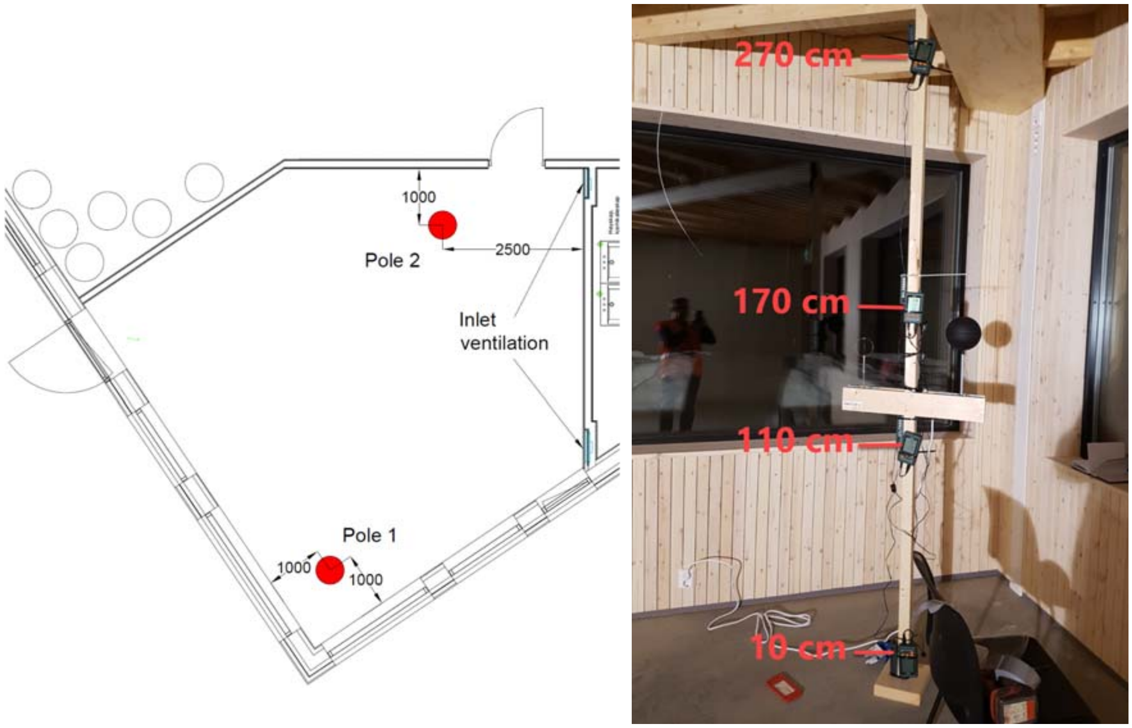

Figure 5. Positioning of the measuring poles and sensors for temperature and CO_2.

The sensors were mounted in the evening on February 7th and the test started at midnight and ended at 15.00 on February 8th. At the start of the test at 24.00 the ventilation system was in heating mode, providing the maximum available amount of air through recirculation with a supply temperature varying between 27,1 and 28,1 °C. When normal operating hours started at 07.30 the recirculation stopped and fresh air was supplied with a supply temperature varying between 16 and 18 °C. According to the outdoor-compensated temperature curves for supply temperature in the building management system, BMS, the supply temperature should have been much higher, about 21 °C. Due to faulty sensors connected to the BMS this was unfortunately not the case.

There is no automatic measuring of the ventilation airflows to the classroom through the building management system, so measurements were performed manually on-site on the two displacement diffusers. The airflow was measured to be approximately 2x260 m^3/h, in total 520 m^3/h. Since there was no continuous measurement of ventilation airflows, it was necessary to make some assumptions regarding the variations in flow during the experiment. It was assumed that during normal operating hours between 08.00 and 15.00 the airflow was 520 m^3/h. Outside operating hours the airflow was assumed to be proportional to the change in central air flows from the air handling unit The central air flows are automatically measured through the BMS. The average airflow outside operating hours was based on this estimated to be 547 m^3/h.

Between 08.30 and 14.30 the students were present in the classroom. The number of students in the classroom varied during the day. The maximum was 19 and the minimum was 13. Between 11.30 and 12.30 there was a long lunch break and the classroom was emptied.

In addition to the occupant load there was some lightning and a few laptops that was on during the experiment.

The day of the experiment was a cloudy day with outdoor temperatures varying between -7 and +3 °C, see figure 6. The solar gain to the room has been roughly estimated by using the solar models implemented in the software SIMIEN 6.009 (SIMIEN, 2018), and based on radiation measurements at a nearby weather station (http://lmt.bioforsk.no/agrometbase/getweatherdata.php).

An overview over all of the internal and external heat gains are shown in figure 6.

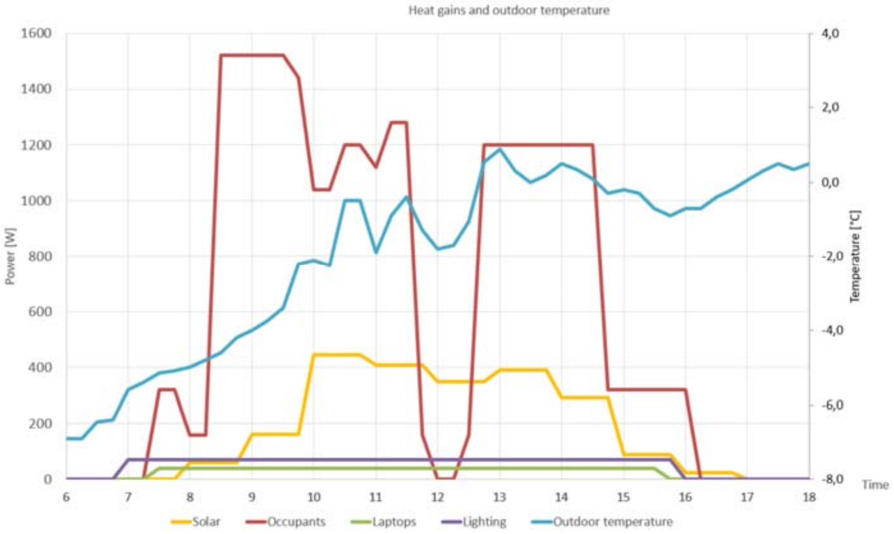

Figure 6: Internal and external heat gains between 06.00 and 18.00.

The heat loss of the classroom is mostly known through rated/calculated U-values and measured air leakage, except for the heat loss through the floor to the ground. Because that the building was completely new, both the temperature in the ground and also the drying-out-process of the floor construction introduce large uncertainties in the estimation of the real heat loss. Based on the measured supplied heat during the heating mode from midnight to 07.00 in the morning, the calculated heat loss through the external walls, windows, door and infiltration and also on accumulated heat in the thermal mass of the room, the net heat loss through the floor was estimated based on a heat balance. The calculated heat loss for the floor was estimated to be 730 W, which was used as an input to the two-zone model.

3 RESULTS AND DISCUSSION

The results from the field experiment are presented in figure 7 and shows that the night heating seems to work. From midnight to 7.30 the room is heated by ventilation with an average supply temperature of 27,5 °C. The results from the measurements in all the different heights shows that the temperature increases during the nighttime.

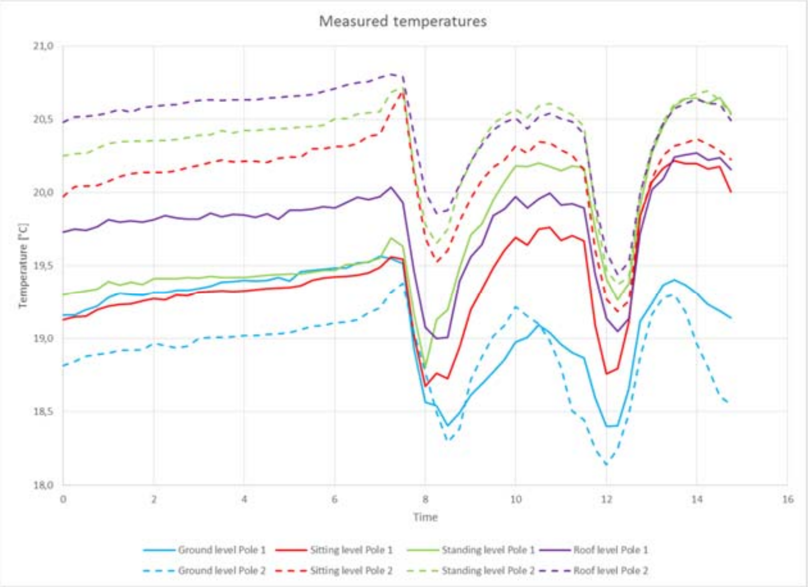

Figure 7: Measured temperature during the field experiment.

To ensure a good displacement ventilation strategy the supply temperature is decreased to a lower temperature than the room temperature during the occupied hours. At 7.30 the ventilation system switches to normal mode with an average supply temperature of 17,3 °C. Because of a lower supply temperature than the room temperature the room is cooled and the only "heating" in the room during the occupied hours is the people and equipment in the room. Between 7.30 and before people enter the room at about 8.30 the room is cooled by ventilation and the temperature drop is 1-1,5 °C. When people enter it takes about 1,5 hour before the temperature stabilize at a temperature between 19-20,5 °C. From about 10 until the break at about 11.30 the temperature is relatively stable. The lower supply temperature during the occupied hours combined with the actual number of people and the airflow according to the CO_2 level seems to create a stable and acceptable temperature in the room.

From the measurements it is also shown that there is a temperature stratification in the room as expected. Due to the displacement ventilation the temperature is lowest in the lower part of the room and rises in the upper part of the room. This is also the case in the heating mode during the night, even though the ventilation heat is supplied to the lower part of the room. This strongly indicate that the supplied heat lead to a plume transferring a large part of the heat to the upper part of the room. However, the stratification in the room is moderate and approximately the same as in the operating hours.

The CO_2 measurements from the field experiments is shown in figure 8. The measurements shows that the CO_2 level during the nighttime is relatively stable and rises when people enters the room. It is also seen that there is a stratification of the CO_2 level in the room during the day.

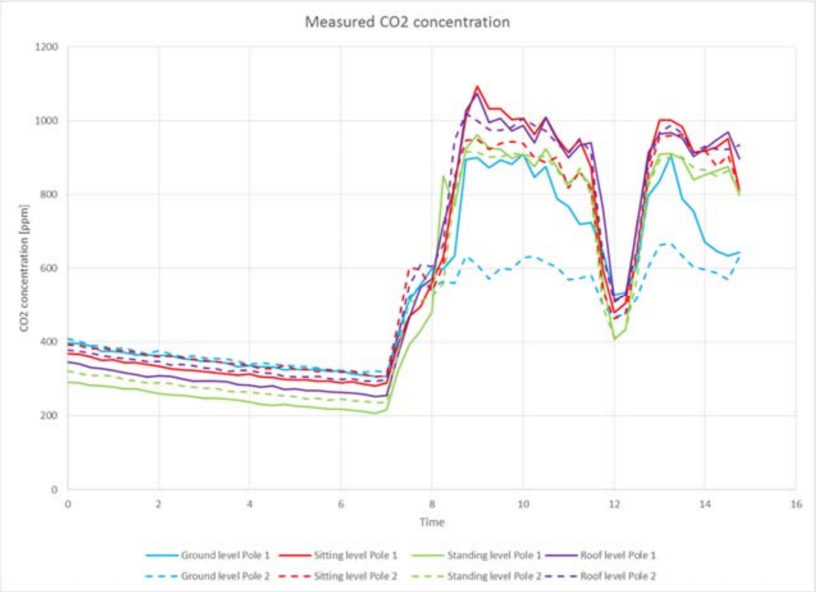

Figure 8: Measured CO2 concentration during the field experiment.

3.1 Temperature stratification – comparison with the two-zone model

The comparison of the measured temperature level from the field experiment and two-zone model is shown in figure 9 and figure 10. The comparison of the two-zone model with the measured data for temperature show that there overall is a good compliance during operating hours.

However, during the night the two-zone model overpredict the temperature in the lower part of the room. The reason for this is that the model is developed on the assumption of supplying cooled air (temperature lower than room temperature) to the lower part of the room, which is opposite of the situation during the night heating mode. To remedy this a “plume-model” for the heated air supply has to be incorporated into the model.

Another issue is that the two-zone model seems to drop faster during the hour before people come (7.30-8.30) and also raise a bit faster than the measured data. This indicate that the thermal mass in the two zone model is underestimated, or that the “access” to the thermal mass through convective- and radiative heat transfer is higher than modelled in the two-zone model. Another possible reason could also be that hygro-thermal processes in the floor slab construction is stabilizing the room temperatures more than it is possible to model with the two zone model.

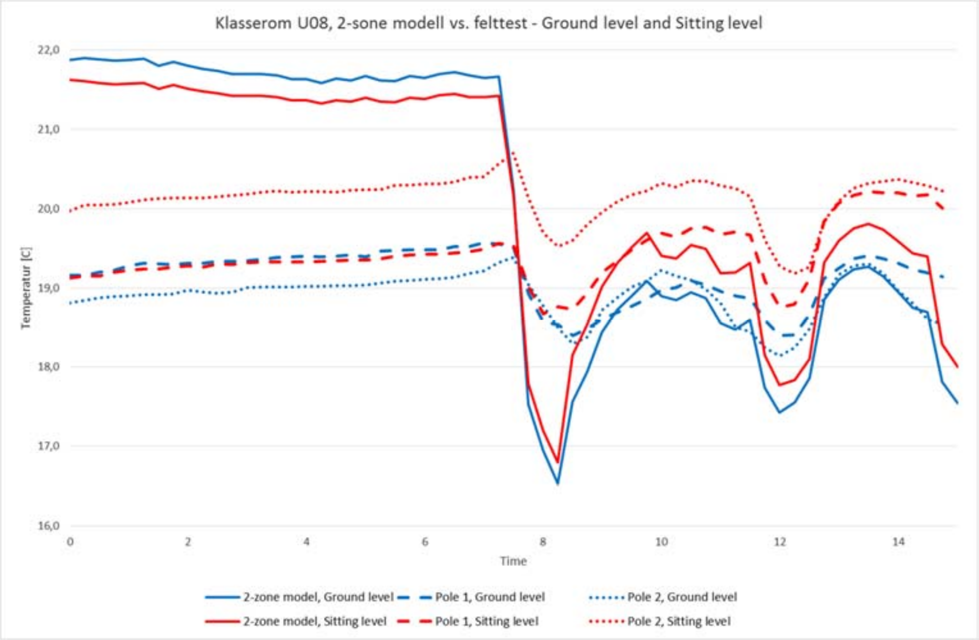

Figure 9: Temperature for two-zone model compared to measured data for ground level and sitting level.

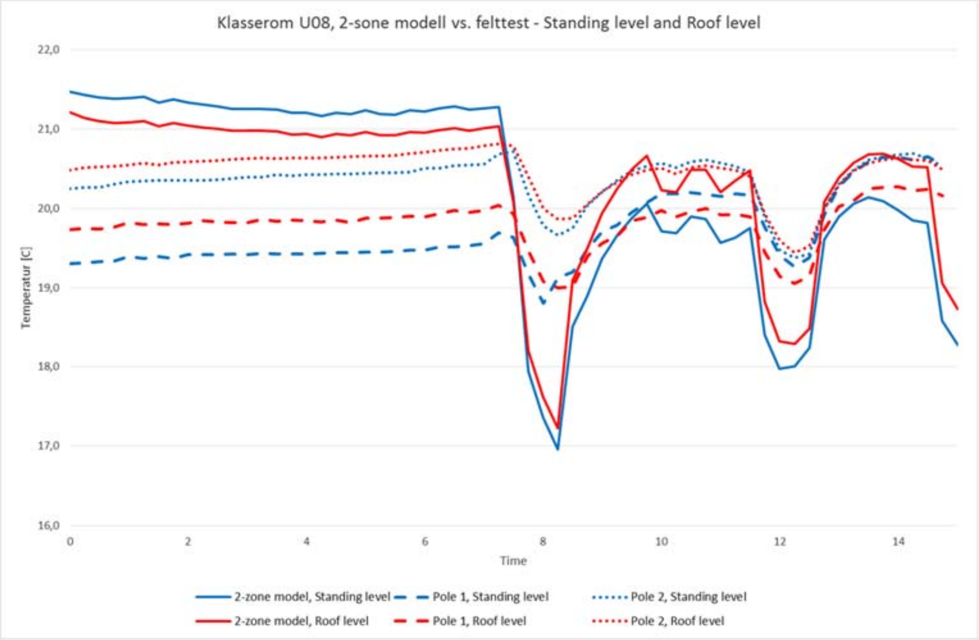

Figure 10: Temperature for two-zone model compared to measured data for standing level and roof level.

3.2 CO2 stratification – comparison with the 2-zone model

The results of the comparison of the two-zone model and the measured data for the CO_2 concentration is shown in figure 11. The measured CO_2 concentration in the exhaust air compared to the calculated CO_2 concentration in the two-zone model shows good compliance.

The measured CO_2 concentration at the ground level varies quite a lot for the two measuring points, Pole 1 and Pole 2. A reason for a higher CO_2 concentration for Pole 1 compared to

Pole 2 might be explained with a higher concentration of people in the area where Pole 1 was placed compared to the area where Pole 2 was placed. Both body movements inducing mixing and release of CO_2 in the lower “clean” zone of the room could explain this effect.

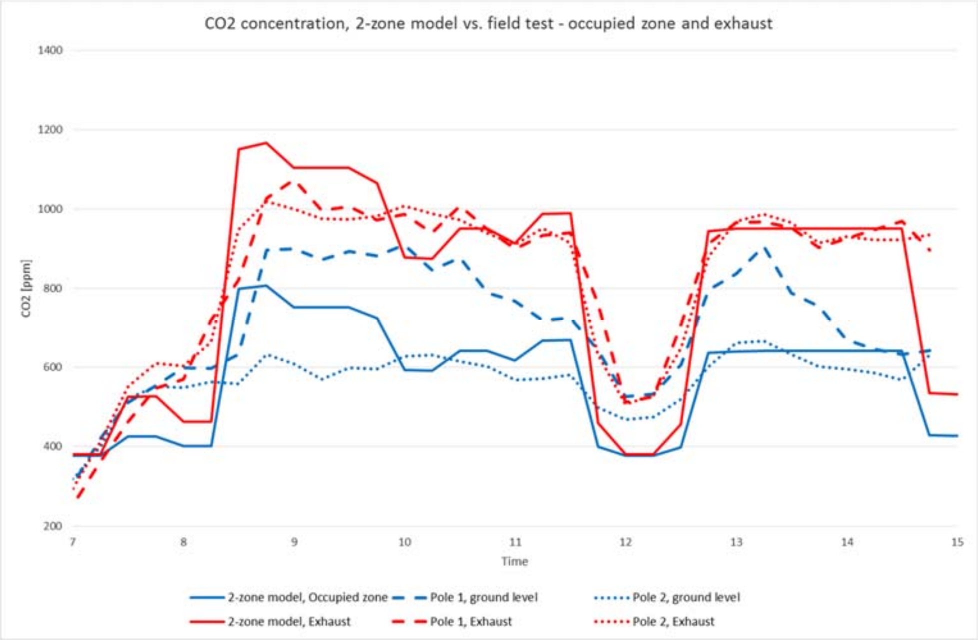

Figure 11: CO_2 concentration for 2-zone model compared to measured data for occupied zone and exhaust.

4 CONCLUSIONS

The measurements from the field experiment and simulations from the two-zone model indicates that the designed system with heating by displacement ventilation during the nighttime with a relatively high supply temperature works. The measurement and simulations also show that there will be a temperature and CO_2 stratification in the room because of the use of displacement ventilation. The two-zone model has to be modified to take into account the night heating mode better. The temperature in the class room seems to be more stable than the model predicts, but this can also be due to complex hygro-thermal processes in the newly built slab on ground construction.

The school opened on the 9th of March 2018 and besides some adjustments in the startup of the ventilation system the users of the building is satisfied with the system.

5 REFERENCES

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