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PERFORMANCE COMPARISON OF AIR DISTRIBUTION SYSTEMS FOR LECTURE ROOM VENTILATION AND THEIR INFLUENCE ON VERTICAL TEMPERATURE GRADIENTS

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SUMMARY

High occupant density, intermittent occupancy patterns, and the impact of classroom environment on teaching and learning, make energy efficient classroom air distribution a challenging task. Performance data of different classroom air distribution systems, during their service life, remains scarce. The current study was hence undertaken to examine performance of three different, demand controlled, air distribution systems, in three in-use lecture rooms: mixed, thermal displacement, and a 50:50 combination of the mixing and displacement schemes. Air temperature and humidity were measured at 20 different heights, at two different locations, in all three rooms. Occupancy was recorded during each scheduled lecture. The vertical temperature gradients varied with air-distribution system type and actual occupancy. Stratification magnitude was remarkably more for the displacement system, compared to the other two. For displacement ventilation temperature stratification was primarily limited closer to the floor. Temperature stratification progressively increased through a class hour, gradually returning towards the initial state once students leave. In the occupied zone, temperature gradients stayed within ~4 °C, thus allaying concerns of local discomfort due to temperature stratification.

Keywords: classrooms, temperature stratification, local discomfort, ventilation,

1 INTRODUCTION

Classroom thermal conditions and air quality have a firmly established relation with student performance (Wargocki & Wyon, 2007; Haverinen-Shaughnessy & Shaughnessy, 2015) and student absenteeism and health (Mendell et al., 2013). At the same time, nature of air distribution system employed in a classroom has a major impact on air quality and distribution and occupant thermal comfort perception (Fong et al., 2011). Fully mixed ventilation (MV) may not be the most efficient when it comes to heat or pollutant removal (Muller et al., 2013). For MV to achieve the same temperature in occupied space as a displacement ventilation system (DV), higher supply air flow rates are typically required, leading to greater energy consumption (Qiu-Wang & Zhen, 2006). Similarly, DV may lead to draft discomfort close to adjacent zone of supply unit and thermal stratification issues. While DV is normally effective in removing pollutants from breathing zone, if there are contaminant sources near the floor, DV may start introducing them into the breathing zone, which could require modifications to the system (Holmberg & Chen, 2003; Kosonen et al., 2017). Yet, data on the performance of air distribution systems in actual classrooms is scarce. Keeping this in mind, a series of measurements were carried out in classrooms on the campus of Aalto University, covering three different systems: MV, DV, and a 50:50 combination of MV and DV. In the current work, we focus on the vertical temperature profiles measured in the three classrooms and and how the temperature profiles are affected by the transitional nature of occupancy. The methods used can inform further studies conducted in field condition to evaluate classroom air distribution systems. Data gathered can also prove to be useful for validating numerical models developed for both energy simulation and CFD models of air distribution.

2 METHODS

2.1 Organization of the measurements

Three classrooms – hereon referred to as R1, R2, and R3 – on the first floor of the Otakari 1 building, in the Otaniemi campus of Aalto University were chosen for these measurements carried out between 27th of October and 1st of December 2017. Classroom relevant features have been summarized in Table 1. Rooms' images and sketched layout have been provided in Figure 1. For all three rooms, exhaust grilles are near ceiling height and located along the back walls. All the rooms have demand based ventilation. The supply air flow rate has maximum value when occupancy sensors detect any presence. But ventilation rate does not change with number of students present. While R3 is a completely internal room, R2 has its west and south walls and R1 has its east and south walls exposed to the outdoors.

Table 1. Classroom Features

Room	Floor Space (m2)	Seating Capacity	Air distribution system	Max. air supply (l/s)	Supply diffusers	Exhaust
R1	94	70	Mixed + Displacement	260 + 500	24 underfloor, 3 in ceiling	4 grilles
R2	156	156	Mixed	1500	3 in ceiling	5 grilles
R3	108	65	Displacement	600	50 underfloor	5 grilles

Table 2. Measuring Instrument

Instrument	Parameters	Range	Accuracy
TinyTag Plus 2 Dual Channel Temperature/RH logger	Temperature Humidity	-25 to 85 °C 0 to 100% RH	0.4-0.5 °C ± 3.0%
Swema 3000md Manometer	Flow differential pressure	-300 to 1500 Pa	±0.3% (> ±0.3 Pa)

Two measuring masts were assembled with 20 TinyTag Plus 2 Dual Channel loggers. Seventeen TinyTags were located at 10 cm separation, starting from 0.1 to 1.7 m, followed by three more at 2, 2.5, and 3 m respectively. An image of this assembled stand has also been given in Figure 1. A Swema 3000md manometer was used for measuring flow rates from individual diffusers. Instrument specifications and accuracy have been provided in Table 2. During measurements, two measuring masts were placed in each classroom. Mast locations have been marked in the layout sketches in Figure 1. One of the masts was kept close to the wall while the other was placed close to the students, to investigate the effect of occupancy and occupancy transitions on the temperature profile. It is data from this second mast that is discussed in this work, the focus being on occupant thermal comfort and implications of stratification and temporal changes in occupancy.

2.2 Analysis of measured data

Data logged by the TingTags were pre-processed and collated using MS Excel 2010. Each room's data was analysed independently. In this work, focus was kept on the vertical temperature profiles for each classroom on the day it had its maximum occupancy during the study. Percentage dissatisfaction due to temperature stratification was calculated using Equation 1 (ISO, 2005), where PD is the percentage dissatisfied and $\Delta T_{a,v}$ is the vertical air temperature difference.

$$PD\ (\%) = \frac{100}{1+\exp(5.76-0.856\cdot\Delta T_{a,v})} \qquad (1)$$

Since occupants were sitting, head height is approximated at 1.1 m and feet are assumed to be at 0.1 m. As the sensor accuracy is 0.4 to 0.5 °C, the accuracy of temperature differences measured is $[(0.5)^2 + (0.5)^2]^{1/2} = 0.7$ °C.

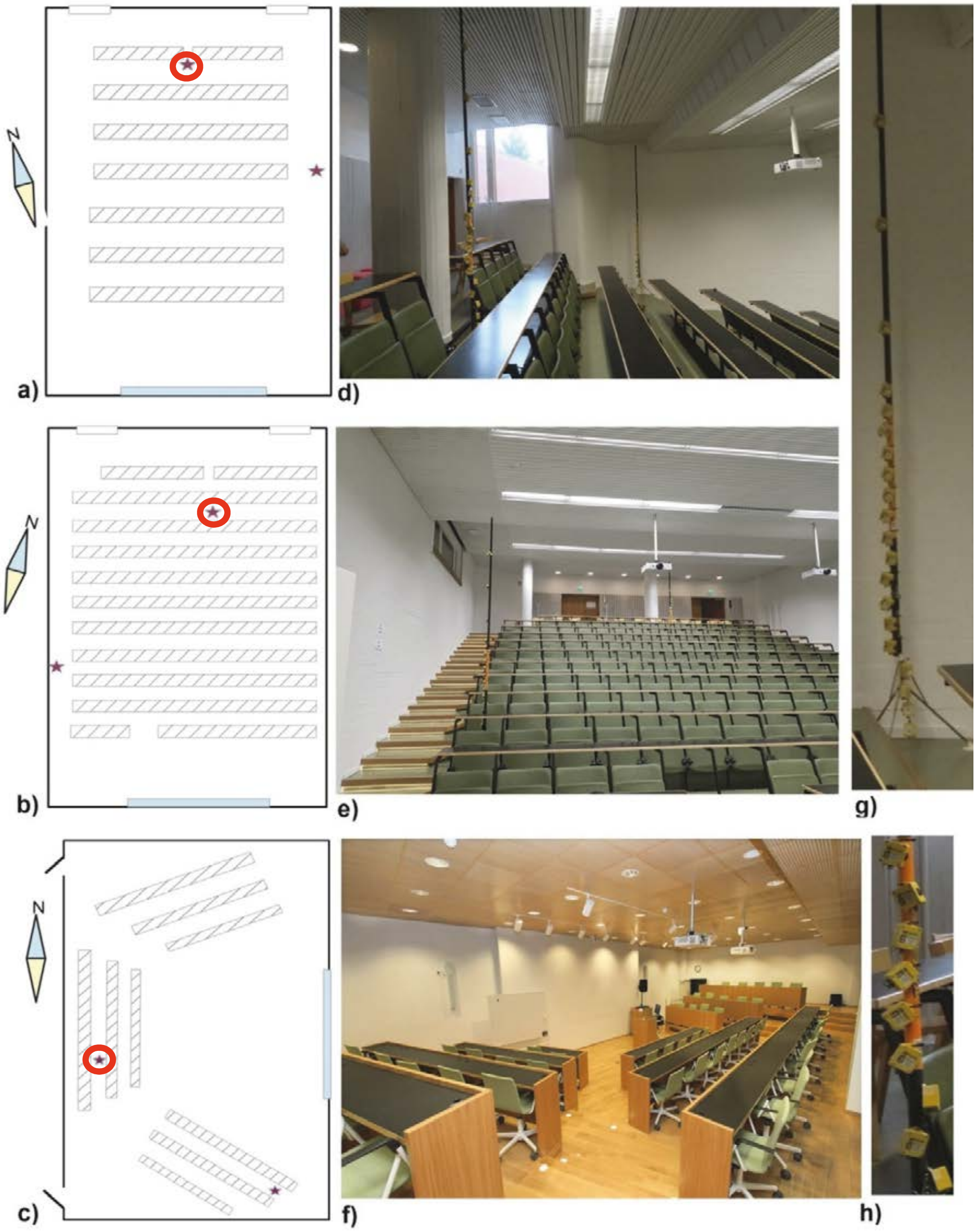

Figure 1. Rooms studied: a) & d) R1; b) & e) R2; c) & f) R3. g) Mast h) close up of sensor arrangement. The stars in the room layout sketches represent where the masts were located during measurements. Results have been presented for the mast location highlighted with a red circle.

3 RESULTS AND DISCUSSIONS

On the days for which we present the data, the occupancy was 54, 60, and 47 students in rooms R1, R2, and R3 respectively. This implies a near 70% occupancy in R1 and R3 but just 38% in R2.

3.1 Temperature profiles in the rooms

The temperature profile, for each of the room, has been presented in Figure 2. Even with the vertical temperature gradient around student sitting locations, temperature for all three rooms, in occupied zone, kept within the design range of 20 to 24.5 °C. Temporal variation of temperature, at the same height, was least for R2 (MV), followed by R1 (MV+DV) and was largest for R3 (DV). Thus, as expected, student influx and exit affected temperature profiles the most for DV and least for MV, with the MV-DV combination being in-between and closer to MV. In R2, even though 66% of the ventilation air came in at floor level, the temperature profiles were closer to that of the MV system. An explanation could be that occupancy was at only 38% of design value, leading to convection flows in the occupied zone being not strong enough.

The temperature ramps in R1 and R3 reached magnitudes of about 1.5 °C per hour at 1.1 m level. Such temperature variations, in classrooms, have not been known to be perceived or cause discomfort (Mishra et al., 2017). For R2, at the same height, temporal variations over an hour were within ranges of instrument accuracy, indicating good mixing in the room space. At any time-point, stratification, for MV, could reach as much as 1 °C (Figure 1 (b)), leading to PD of 0.7%, using Equation 1. For the MV-DV combination, stratification always kept within 0.5 °C (Figure 1 (a)), i.e., within the limits of instrument accuracy. For the DV room, stratification was the most conspicuous and by the end of the lecture, temperature difference between head and feet levels reached 3.4 °C (Figure 1 (c), 11:00), indicating a PD of 5.5%. Some points at below 0.5 m height in R3 could have temperature in the range of 19.5 to 20 °C, raising concerns of cold discomfort for lower body parts. Stratification increased as students come in and reached the maximum level at the end of lectures. As expected, the most conspicuous example of this evolution of vertical temperature profiles was the DV room. Once the lecture is over and students start exiting, the temperature profiles started moving back towards the ones prevalent in the unoccupied classroom.

The three air distribution systems presented distinct vertical temperature profiles. The MV-DV combination led to vertical temperature profiles closer to MV but temporal variations similar to the DV case. Stratification magnitude in DV could pose some risks of local discomfort due to vertical temperature gradients, especially towards the end of the lecture. The MV-DV system produces vertical temperature profiles with very little stratification. This may be attributed to air streams, at similar temperatures, being introduced from both the ceiling and floor.

The MV-DV is an interesting example since it may not be planned as part of initial construction but retrofits, requiring higher ventilation rates, may lead to this curious combination. More such systems would be encountered as existing building get retrofitted and ventilation requirements are revised. Performance of MV-DV system needs more extensive examination and further careful consideration of its control strategy – for example, what fraction of air needs to be introduced from ceiling diffusers, depending on occupancy. In addition to the temperature stratification, the other aspect of note was temporal variations in temperature and vertical temperature profiles. Temperatures were within winter comfort limits. But, if a conditioning system is maintaining temperatures closer to the upper thermal comfort limit, overheating may become an issue. This is an aspect typical to classrooms because of the transitional nature of occupancy and high occupant density. Keeping these occupancy related aspects in mind, we had focused measurement location close to student seating positions.

3.2 Study Limitations

The classrooms were of different sizes and different actual occupancy, making an unbiased comparison of the air distribution systems difficult. The classrooms had a few other differences, including orientation and external walls and windows. However, each of the classrooms is quite large (90 m^2 or larger) and held over 50 students during the measurements discussed. Keeping these differences in mind, discussions have been limited to temperature profile near student seating positions. The type of load has a significant effect on temperature gradients (Muller et al., 2013;

Kosonen et al., 2017). In most cases, the major portion of thermal gradient occurs within the occupied zone, as does it in this case as well. However, additionally, there were also some significant gradients between 2 and 3 m. This may be attributed to the positioning of light fixtures.

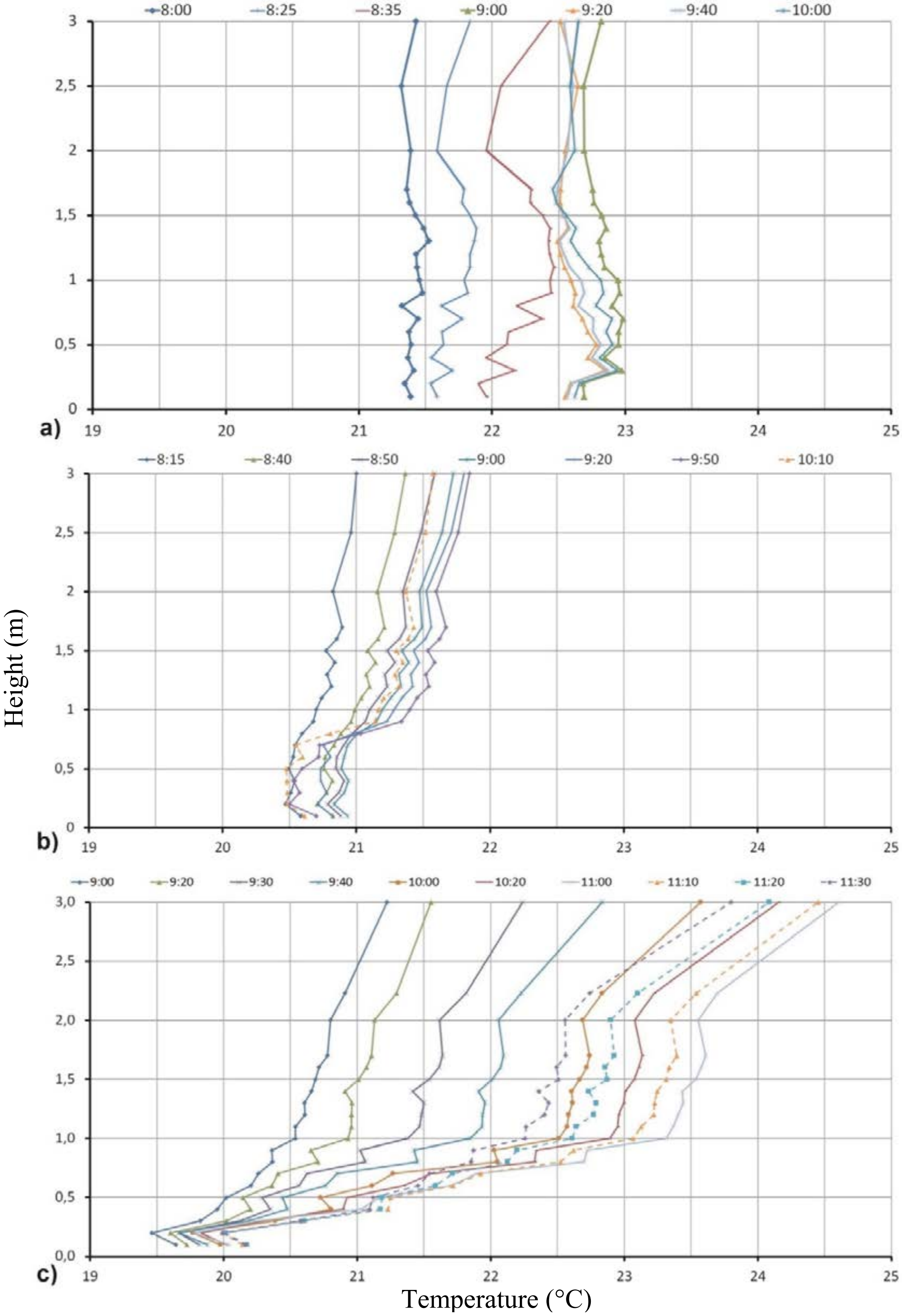

Figure 2.Vertical temperature profiles in the investigated rooms on the day when maximum occupancy was observed for each room. Vertical temperature profiles at different time points, from beginning to end of lecture, have been provided: a) R1; b) R2; c) R3

5 CONCLUSIONS

While temperature stratification due to DV and MV systems is a well explored subjected, in this work, we have touched upon two other compelling aspects: a hybrid of DV-MV systems for air distribution and the temporal variations due to transient occupancy. Our results showed that vertical variations are dependent on the ventilation type but all three systems had temporal variations that tracked the student influx and exit patterns. Unlike the DV or MV system, even though 66% of the supply air is released in the occupied zone, MV-DV showed very little stratification of air temperature. For the DV system, some risks of local discomfort due to vertical temperature gradients and draft exposure to lower body parts were noted.

The study also yielded a significant volume of practical data on performance of three different air distribution systems in classrooms. While we have focused on aspects of temperature stratification and temporal variations due to occupancy in this work, successive works would be presenting more detailed analysis and other aspects of temperature variations across the classrooms.

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