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Field Comparison Study of Indoor Environment Quality in Office Buildings with Underfloor and Overhead Ventilation Systems

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ABSTRACT

The use of UFAD (Underfloor Air Distribution) systems is increasing rapidly and reported advantages of UFAD include energy savings and improved indoor air quality. At present few publications documenting measurements of ventilation effectiveness and indoor environment quality in occupied buildings with UFAD have been identified. In this field comparison study we measured several aspects of the thermal environment in two buildings with different ventilation systems (under-floor air distribution and mixing) located in Montréal (Québec). The results are presented in terms of thermal stratification, predicted thermal comfort indices (VATD, limit to air speed and PMV/PPD), and IAQ index (CO_2 level and stratification). The aim of the study was to determine whether UFAD in practice results in improved ventilation effectiveness compared to typical overhead air distribution without affecting the thermal comfort. The study found that there was little stratification for UFAD under operating conditions and it performed as a mixing system, thus no improvement in ventilation effectiveness was identified in the occupied zone, in comparison to the reference mixing system. In addition the predicted thermal comfort in terms of VATD, air speed and PMV/PPD was similar to those obtained for mixing ventilation and was within the acceptable limits set by ASHRAE 55-2010.

INTRODUCTION

Buildings are designed, constructed and operated to provide safe, secure, and healthy indoor conditions, and facilitate the well-being and productivity of occupants. HVAC systems are of primary importance for buildings since indoor environment parameters such as thermal comfort and air quality rely on the effective operation of the air distribution (mixing/stratified) systems. Following the introduction of heating, ventilation and air-conditioning (HVAC) systems in buildings, the vast majority of designs have been of a 'mixing type'. The main objective of mixing ventilation is to efficiently mix supply air with room air. Contaminants and heat in the room are diluted by supply air and then extracted through the return grille. Stratified ventilation systems, such as underfloor air distribution (UFAD), are becoming popular in modern buildings (Bauman 2003). Such systems supply air at floor level and return air near or at ceiling level and have several advantages over conventional ceiling supply/return system, they can achieve: improvements in the ventilation efficiency, and better indoor air quality at breathing level (Chen and Glicksman 2003, Bauman 2003). These systems can also achieve energy savings as the ventilation air is not heated to as high temperature as that in mixing ventilation (Chen et al. 2003).

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Compared to mixing room air distribution UFAD does not mix heat and contaminants, instead displacing them from the breathing zone into the upper zone, where they are extracted as shown in Figure 1. To achieve this flow UFAD room air distrinution needs to generate a temperature and contaminant gradient or stratification in the room. This results in warmed contaminants rising to the ceiling level while cooler supply air is delivered at floor level. The use of UFAD is increasing rapidly (Bauman et al. 2001). However, there are few publications documenting measurements of ventilation effectiveness and thermal comfort in buildings with UFAD.

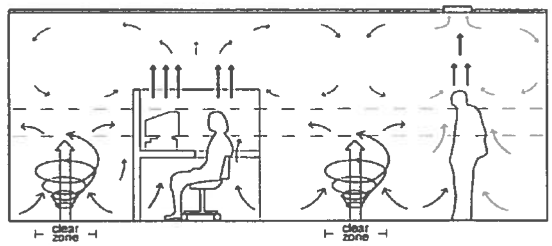

Figure 1. Underfloor air distribution system with diffusers throws.

The primary objectives of this study are to determine whether UFAD in practice results in improved ventilation effectiveness compared to mixing ventilation (implying improved indoor air quality in the occupied zone) and differences in the predicted thermal comfort. A secondary objective of this study is to add to the limited information on the thermal stratification and thermal comfort in occupied buildings with UFAD. This paper presents results from two sets of field measurements (fall and winter) from a building equipped with UFAD system compared to a building with a mixing ventilation system. The performance of the whole HVAC system is not discussed. The detailed description of monitored spaces, measurement methodology and results are discussed.

STUDY BUILDINGS

Thermal environments, predicted thermal comfort, and ventilation effectiveness of UFAD system were measured and evaluated in an office building (Building B) with comparison of a mixing system in a second office building (Building C).

Building B is a public library (Bibliothèque et Archives nationales du Québec) located in downtown Montréal. The library is a four storey building built in 2002. The building is equipped with an underfloor air distribution system and an HVAC system with multizone variable air volume (VAV). Mechanical air supply is delivered to the space through floor diffusers of swirl type with the exhaust air grilles located in the ceilings. Each diffuser has damper, which is controlled (open or closed) by wall-mounted thermostat. The diffusers are controlled in sequence to satisfy the cooling demand. The field measurements took place on the fourth floor which is an open concept office space (cubicles) area. The fourth floor of this building, which contained our study sites, has a ceiling height of 2.6 m (8.5 ft) at the building core and perimeter.

Building C is a conservation centre owned by the public library. The building is located in Jean Talon residential area in the north of Montreal Island. The building is a two storey building with a constant air volume mixing ventilation system. Mechanical air supply is delivered to the space through ceiling diffusers with the exhaust air grilles located in the ceilings too. The field measurements took place on the second floor which is an open concept office (cubicle) space area. The second floor of this building, which contained our study sites, has a ceiling height that ranged from 3.3 m (10.8 ft) at the building perimeter to a maximum of 4.4 m (14.4 ft) at the building core.

FIELD MEASUREMENT PROCEDURE

The performance assessment of the UFAD and Mixing systems consisted of monitoring periods from one to two hours that took place in two pre-selected spaces located in core and perimeter area of the study buildings. The fall seasonal field studies took place in early December 2012 and winter seasonal field studies took place in February 2013. The HVAC systems of both building were working in heating mode for both field studies. Data on the monitored locations (core and perimeter zones) in the two buildings in terms of occupancy, nearest supply air temperature and return air temperature, and corresponding outdoor temperatures and weather condition (at time of measurement) are listed in Table 1. The plans of the monitored floors amd measurement locations (core zone and perimeter zone) are shown in Figure 2.

Table 1. Monitored buildings/zones.

Season	Fall		Winter		Fall		Winter	
Building	B		B		C		C	
Ventilation system	UFAD		UFAD		Overhead		Overhead	
Diffuser location	floor		floor		ceiling		ceiling	
Return location	ceiling		ceiling		ceiling		ceiling	
Zone	perimeter	core	core	perimeter	perimeter	core	core	perimeter
Ceiling height [m/ft]	2.6/8.5		2.6/8.5		4.5/14.7		4.5/14.7	
# of occupants	10	5	6	9	6	3	6	3
Supply T [°C/°F]	20.9/69.6	20.3/68.5	22.4/72.3	22.0/71.6	24.5/76.1	23.7/74.7	23.6/74.5	24.6/76.3
Return T [°C/°F]	22.5/72.5	22.3/72.1	23.2/73.8	22.7/72.9	24.4/75.9	23.8/74.8	23.8/74.8	24.6/76.3
Outdoor T [°C/°F]	10.4/50.7	10.8/51.4	-0.5/31.1	0.3/32.5	2.1/35.8	-0.4/31.3	2.2/36.0	2.5/36.5
Weather	cloudy	cloudy	snow	cloudy	Snow	cloudy	cloudy	cloudy

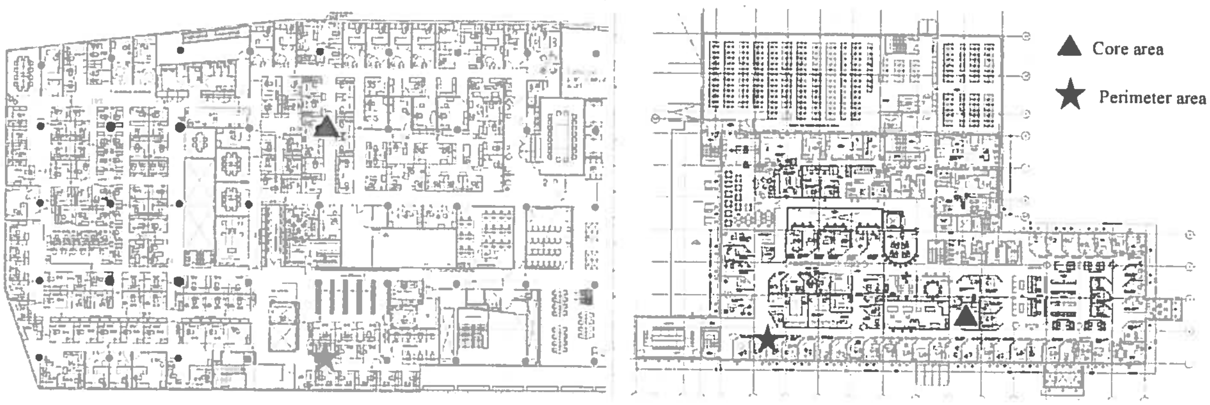

Figure 2. Monitored floor plans - Building B (left side) and in Building C (right side).

Measurements were carried out in line with ASHRAE Standards 113-2005, 55-2010 and 129-1997. The major measurement objectives were to determine the ventilation efficiency as indicated by the contaminant removal effectiveness for carbon dioxide, to quantify the extent of vertical stratification, and to assess the predicted thermal comfort. The measured parameters, measurement location, instrumentation and analysis are described below. The sensors used to measure air speed, dry bulb air temperature, globe temperature (GT) using an RTD sensor installed in black sphere, relative humidity and CO_2 concentration were attached to a sensor holder. Each sensor cluster was located on poles at specific heights above the floor as presented in Table 2. The accuracies of the sensors met the requirement set by related ASHRAE standards. All sensors were calibrated before each field study and their specifications are presented in Table 3. Sampling from all sensors occurred at an interval of three seconds, averaged over 3-minutes periods for an average total duration of up to two hours.

ANALYSIS

The indoor environment with UFAD and mixing ventilation was assessed using the following criteria:

- Predicted thermal comfort – vertical air temperature difference (evaluated according to ASHRAE 55-2010).
- Predicted thermal comfort – limit to air speed (evaluated according to ASHRAE 55-2010).
- Predicted thermal comfort – predicted mean vote (PMV)/percentage people dissatisfied (PPD) (evaluated according to ASHRAE 55-2010).
- Indoor air quality – CO_2 concentration (evaluated according to ASHRAE 62.1-2010).

Table 2. Measured variables and locations.

Sensor Location	Cluster #	Sensor type	Location (above floor level) [m/ft]			
			Building B		Building C	
			Core	Perimeter	Core	Perimeter
Main Pole	1	RTD, Anemometer	0.1/0.3	0.1/0.3	0.1/0.3	0.1/0.3
	2	RTD, GT, RH&T, Anemometer	0.6/2.0	0.6/2.0	0.6/2.0	0.6/2.0
	3	RTD, GT, RH&T, Anemometer	1.1/3.6	1.1/3.6	1.1/3.6	1.1/3.6
	4	RTD, CO_2, Anemometer	1.7/5.6	1.7/5.6	1.7/5.6	1.7/5.6
	5	RTD, CO_2, Anemometer	2.45/8.0	2.45/8.0	2.2/8.0	2.2/8.0
	6	RTD	-	-	3.4/11.2	3.0/9.8
Return Pole	7	RTD, CO_2	2.6/8.5	2.6/8.5	4.4/14.4	4.4/14.4
Supply Pole/Cluster	8	RTD, CO_2	0.0/0.0	0.0/0.0	4.4/14.4	4.4/14.4
Reference Pole	9	RTD, RH&T	1.1/3.6	1.1/3.6	1.1/3.6	1.1/3.6
Floor	10	RTD	0.0/0.0	0.0/0.0	0.0/0.0	0.0/0.0

Table 3. Specifications of used sensors.

Sensors (Quantity)	Type	Range	Accuracy (Precision)
Air temperature (10)	RTD	-10 – +40°C	0.1°C
CO_2 concentration (5)	GMD20/D	0 – 2000 ppm	40 ppm
Air speed (5)	Omnidirectional	0.01 – 1 m/s	±0.5% (0.05 m/s)
Relative humidity (3)	RH&T	10 – 90%	3%

RESULTS

Thermal Stratification

Typical examples of the profile of air temperature with height, based on three minutes averaged temperature for a minimum of one-hour periods are presented in Figure 3. Figure 3 (left side) provides a typical example of the profile of air temperature with height for both core and perimeter zones in Building B. In this figure, the temperatures at a height of 0.1 m (0.3 ft) represent the temperatures of the supply air and those at a height of 2.6 m (8.5 ft) represent the temperatures of the return air. At the core and perimeter sites, the temperatures increased 2 °C (3.6 °F) or less between the supply and height of 0.1 m (0.3 ft), and then increased less than 1 °C (1.8 °F) in the occupied zone between heights of 0.1 m (0.3 ft) and 1.7 m (5.6 ft).

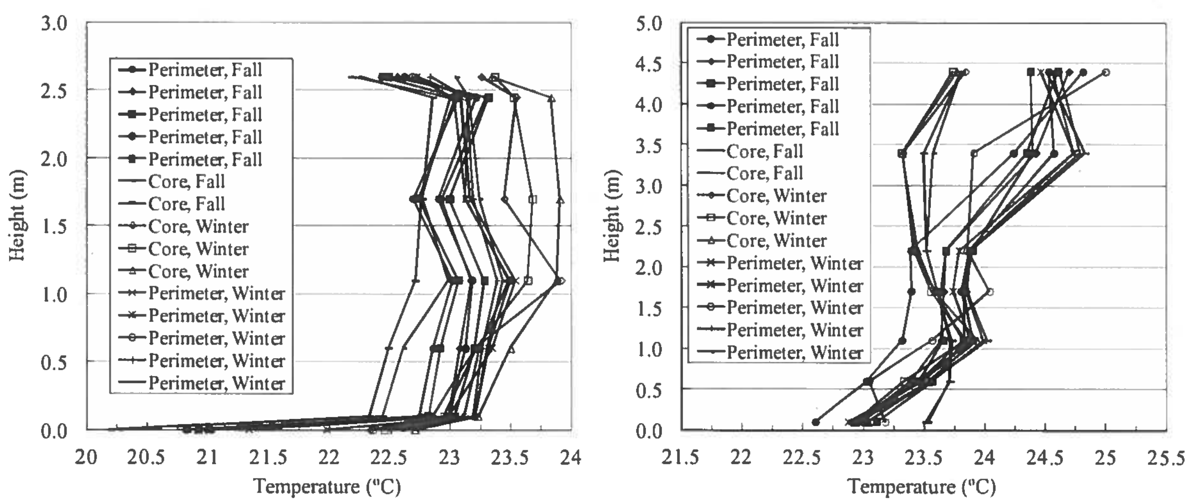

Figure 3. Examples of vertical air temperature profiles in Building B (left side) and in Building C (right side).

Figure 3 (right side) provides an example of the profile of air temperature with height for both core and perimeter zones in Building C. In this figure, the temperatures at a height of 4.4 m (14.4 ft) represent the temperatures of the supply and reurn air. At the core and perimeter sites, the temperatures increased 1 °C (1.8 °F) or less between the height of 0.1 m (0.3 ft) and the the return located at the ceiling height of 4.4 m (14.4 ft). The two buildings had similar thermal load (equipment and occupant), however the ceiling height was larger in building C with ceiling-based ventilation (with greater thermal stratification) than builing B with floor-based ventilation system. Table 4 indicates the degree of indoor temperature stratification at each measurement building and site. The numbers in the table are time averages for all monitoring period of measuremnts.

Table 4. Summary of the mean vertical temperature stratification.

Season	Buidling	Zone	$T_r - T_s$ [°C/°F]	$T_r - T_{0.1m}$ [°C/°F]	$T_{1.7m} - T_{0.1m}$ [°C/°F]	$T_{1.1m} - T_{0.1m}$ [°C/°F]
Fall	B	Perimeter	1.6/2.9	-0.4/-0.7	0.0/0.0	0.3/0.5
		Core	2.0/3.6	-0.2/-0.4	0.3/0.5	0.4/0.7
	C	Perimeter	0.0/0.0	1.7/3.2	0.7/1.3	0.7/1.3
		Core	0.0/0.0	0.3/0.5	0.1/0.2	0.3/0.5
Winter	B	Perimeter	0.8/1.4	-0.3/-0.5	0.1/0.2	0.4/0.7
		Core	0.8/1.4	0.3/0.5	0.7/1.3	0.8/1.4
	C	Perimeter	-0.1/-0.2	1.6/2.9	0.9/1.6	1.0/1.8
		Core	0.1/0.2	0.8/1.4	0.6/1.1	0.9/1.6

In absolute terms, the extent of temperature stratification was higher in building C than in building B. In building B with the UFAD system, the air temperature at the return grille was less than 0.5 °C (0.9 °F) higher than the temperature just above the floor at a height of 0.1 m (0.3 ft). The temperature difference between the supply air and nearby return air grille was only 0.8 to 2.0 °C 1.4 to 3.6 °F) in building B; thus, the degree of temperature stratification in the occupied space was small. The temperature difference between the supply air and nearby return air grille measured in building C was close to 0.0 °C (0.0 °F), showing uniform air temperature in the occupied space.

Predicted Thermal Comfort

Since UFAD supplies air at temperature lower than room air temperature and directly to the occupied zone, temperature stratification may cause discomfort. Thermal stratification results in warmer air temperature at head level in comparison to that at ankle level. The measured values of thermal comfort index VATD in building B and C during fall and winter season at seated breathing height (1.1 m/3.6 ft) and standing breathing height (1.7 m/5.6 ft) are presented in Table 5.

Table 5. Summary of measured thermal comfort index VATD (°C/°F).

Season	Buidling	Zone	Height	Mean	STDV	Minimum	Maximum
Fall	B	Perimeter	1.1 m (3.6 ft)	0.4/0.7	0.08/0.14	0.1/0.2	0.5/0.9
			1.7 m (5.6 ft)	0.0/0.0	0.06/0.11	0.0/0.0	0.1/0.2
		Core	1.1 m (3.6 ft)	0.4/0.7	0.06/0.11	0.4/0.7	0.6/1.1
			1.7 m (5.6 ft)	0.3/0.5	0.06/0.11	0.2/0.4	0.4/0.7
	C	Perimeter	1.1 m (3.6 ft)	0.7/1.3	0.06/0.11	0.7/1.3	0.9/1.6
			1.7 m (5.6 ft)	0.7/1.3	0.05/0.10	0.7/1.7	0.8/1.4
		Core	1.1 m (3.6 ft)	0.3/0.5	0.05/0.10	0.2/0.4	0.3/0.5
			1.7 m (5.6 ft)	0.1/0.2	0.04/0.07	0.1/0.2	0.2/0.4
Winter	B	Perimeter	1.1 m (3.6 ft)	0.4/0.7	0.16/0.29	0.2/0.4	0.8/1.4
			1.7 m (5.6 ft)	0.1/0.2	0.10/0.18	-0.1/-0.2	0.3/0.5
		Core	1.1 m (3.6 ft)	0.8/1.4	0.13/0.23	0.6/1.1	1.1/2.0
			1.7 m (5.6 ft)	0.7/1.3	0.06/0.11	0.6/1.1	0.8/1.4
	C	Perimeter	1.1 m (3.6 ft)	1.0/1.8	0.08/0.14	0.8/1.4	1.1/2.0
			1.7 m (5.6 ft)	0.9/1.6	0.05/0.10	0.8/1.4	1.0/2.0
		Core	1.1 m (3.6 ft)	0.9/1.6	0.06/0.11	0.8/1.4	1.0/2.0
			1.7 m (5.6 ft)	0.6/1.1	0.05/0.10	0.5/0.9	0.7/1.3

The measured VATD in the two buildings during fall and winter seasons complies with the maximum acceptable 3 K (5.4 °F) set by ASHRAE 55-2010. The maximum value of VATD in building B with UFAD was 1.1 K (2 °F), showing a possibility to lower the supply air temperature without exceeding the limit of 3 K (5.4 °F).

Stratified systems such as UFAD are perceived by some to increase the risk of excessive draft, because of the close proximity of supply outlets to the occupants compared to mixing systems where the supply is at the ceiling far from occupants. Typical examples of the profile of air speed with height are presented in Figure 4.

Figure 4 (left side) provides examples of air speed profiles for both core and perimeter zones in Building B and Figure 4 (right side) provides profiles of air speed in building C. The measured air speeds in the two buildings during fall and winter season were generally lower than 0.15 m/s (29.4 ft/min) in the occupied zone and comply with the limit to air speed set by ASHRAE 55-2010.

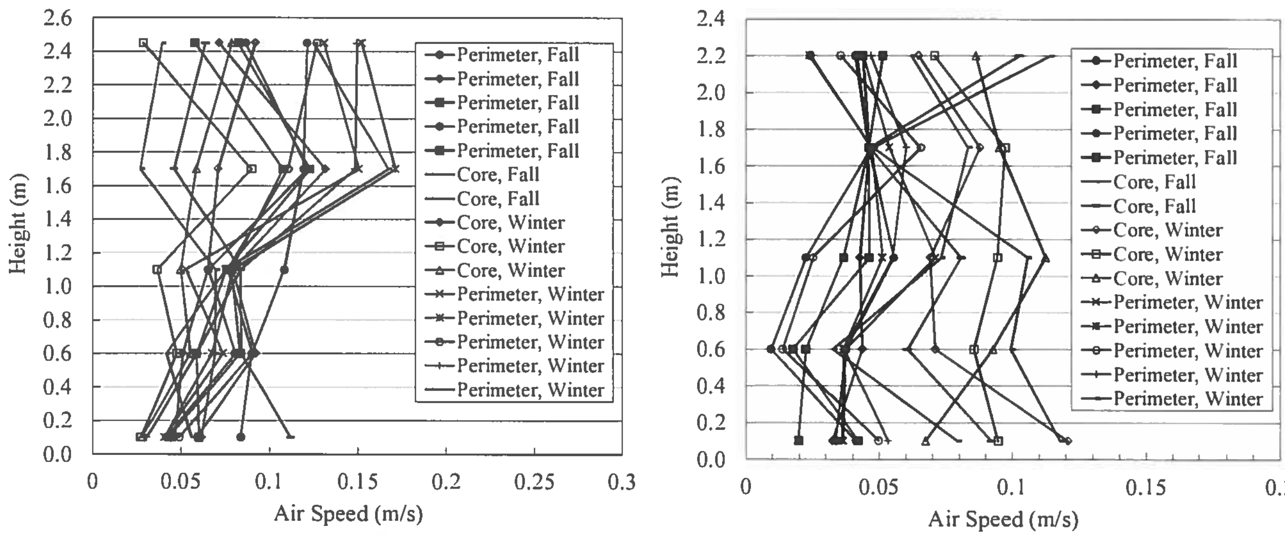

Figure 4. Examples of vertical air speed profiles in Building B (left) and in Building C (right).

The PMV and PPD values were calculated assuming 1.0 clo and 1.1 met, and at 0.6 m (2.0 ft) height for a seated person and 1.1 m (3.6 ft) height for a standing person in both core and perimeter zone of the two monitored buildings B (UFAD) and C (overhead). The resulting predicted mean vote and predicted percentage dissatisfied values generated by the model during fall and winter season are presented in Table 6. The generated values for buildings, zones and seasons were within the recommended ranges set by ASHRAE 55-2010. The conditions on the 4th floor of building B with the UFAD system and in the 2nd floor of building C with the mixing ventilation system were within the comfort zone.

Indoor Air Quality

Table 7 indicates the degree of indoor CO_2 stratification of indoor environment at each measurement location and building. The numbers in the table are time averages for the entire monitoring period of measuremnts. All of the mean values of CO_2 concentration in occupied zone were less than the 700 ppm above outdoor concentration (~450 ppm), limit set by ASHRAE 62.1-2010. The CO_2 concentration differences between the supply air and nearby return air grille measured were within the accuracy of the CO_2 sensor (+/- 40 ppm), showing uniform CO_2 concentration in the occupied space. This would indicate that the UFAD system in building B was performing as a mixing system, similar to mixing system in Building C.

Table 6. Summary of calculated thermal comfort indices PMV and PPD.

Season	Buidling	Zone	PMV/PPD	Mean	STDV	Minimum	Maximum
Fall	B	Perimeter	PMV	0.1	0.03	0.0	0.2
			PPD	5	0.13	5	6
		Core	PMV	0.0	0.04	-0.1	0.1
			PPD	5	0.07	5	5
	C	Perimeter	PMV	0.2	0.01	0.1	0.2
			PPD	6	0.09	5	6
		Core	PMV	0.1	0.07	-0.1	0.2
			PPD	5	0.24	5	6
Winter	B	Perimeter	PMV	0.2	0.02	0.1	0.2
			PPD	6	0.14	5	6
		Core	PMV	0.2	0.04	0.1	0.3
			PPD	6	0.30	5	7
	C	Perimeter	PMV	0.1	0.03	0.0	0.2
			PPD	5	0.15	5	6
		Core	PMV	0.1	0.04	-0.1	0.2
			PPD	5	0.10	5	5

Table 7. Summary of the mean CO_2 concentration and stratification.

Season	Buidling	zone	C_s [ppm]	C_{oz} [ppm]	C_r [ppm]	$C_r - C_s$ [ppm]	$C_r - C_{1.1\,m}$ [ppm]	$C_r - C_{1.7\,m}$ [ppm]	$C_r/C_{avg,oz}$
Fall	B	Perimeter	461	494	473	12	-30	-13	0.96
		Core	448	484	487	39	-3	10	1.01
	C	Perimeter	454	437	434	-21	-12	5	0.99
		Core	473	455	456	-17	-8	10	1.00
Winter	B	Perimeter	550	579	591	41	2	24	1.02
		Core	504	622	573	69	-54	-45	0.92
	C	Perimeter	477	481	451	-26	-16	6	0.94
		Core	446	458	438	-8	-13	3	0.96

DISCUSSION

A primary objective of this study was to compare the performance of a UFAD system with a mixing ventilation system in occupied office buildings.

The measured increase in indoor temperature between locations just above the floor and the reurn air grilles was small in both buildings, always less than 1.7 °C (3.1 °F) in building C and 0.5 °C (0.9 °F) in building B. The combination of low internal thermal loads, ceiling height lower than 3 m (9.8 ft), failrely high supply air temperature and moderate supply air flow rates in the study building B with UFAD were such that one could not expect a large amount of vertical thermal stratification. Measurements of temperature gradients under conditions with heating showed that heating of a building B with the UFAD system caused less thermal stratification than heating of building C with the mixing air distribution system that supplies and removes warm air at the ceiling. However, lower supply air temperature (18 – 20 °C/64.4 – 68 °F) could have increased the temperature stratification in building B leading to stronger vertical displacement (contaminant transport towards ceiling) and potential energy saving.

The CO_2 concentration results from Building C with the mixing ventilation system were expected to be uniform with height, but not for building B with the UFAD system. The measurements indicate that the UFAD system was not working correctly in terms of contamiant stratification, potentially caused by low internal heat loads, not strong enough to create floor-ceiling contaminant stratification given the supply volume. Thus, this study did not identify an improvement in ventilation effectiveness or IAQ-related benefits with UFAD in the occupied zone. However, with different UFAD equipment or operating conditions, such as lower supply air temperatue, or flow rate, or higher internal thermal loads, it is possible that the UFAD system performance could result in improved ventilation effectiveness. Unfortunately, in the study building B it was not possible to make any changes to the HVAC system. However, the predicted thermal comfort was not significantly different from those obtained for mixing ventilation and was within acceptable limits sets by ASHRAE 55-2010.

CONCLUSION

Comparative measurements of space thermal and indoor environment quality were taken in two occupied office buildings located in the city of Montréal. The key difference between the two buildings was that one building employed a mixing ventilation system and the other a UFAD system. The main findings were as follows:

- Overall, the fall and winter field studies showed that building B (with UFAD) and building C (with mixing) performed equally well in terms of thermal comfort indices and CO_2 levels in the occupied zone.
- The measurements in Building B with UFAD ventilation system showed little floor-ceiling contaminant stratification. This is typical of a mixing system thus potential improvement in ventilation effectiveness and IAQ in the occupied zone were not observed.

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