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Field Measurements of Air Change Effectiveness Using Tracer Gas Techniques.

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ABSTRACT

The present paper reports on tracer gas measurements performed in five large buildings during normal operating conditions. In all buildings air was supplied through ceiling diffusers and returned through a ceiling plenum. The measurements were taken during summer with the systems in cooling mode, i.e. the supply temperature was lower than the room temperature.

The global air change effectiveness and the occupied zone average air change effectiveness were calculated based on the age-of-air concept. The local air change effectiveness i.e., for one point in the space, was calculated in two ways: (1) Age-of-air in the return duct divided by local age-of-air at breathing level, and (2) Age-of-air at return grille in ceiling divided by local age-of-air at breathing level. To measure age-of-air the tracer gas step-up method was used.

The global air change effectiveness as well as the average air change effectiveness in the occupied zone for all systems indicated complete mixing. The local air change effectiveness showed, however, larger differences, indicating that the air in the occupied zone was not uniform mixed in all buildings.

INTRODUCTION

The cause for many cases of Sick Building Syndrome is often poor ventilation: either a low level of outdoor air coming into the building or poor distribution of the air in the system or in the occupied space. The distribution of the air influences both the thermal conditions and the indoor air quality in the space. Therefore, it is important to know how efficient the air is being distributed in the space. Also, from an indoor air quality standpoint, it is important to know how efficient contaminants are being removed from the occupied zone. These two factors are often described as air change effectiveness (efficiency of the air distribution) and contaminant removal effectiveness (Brouns 1991) (efficiency of contaminant removal).

This paper presents measurements of air change effectiveness performed in several large buildings. The intention is to contribute to the knowledge about air change effectiveness in typical buildings during typical summer conditions, and not to study the influence of the type of building or system. Other studies that report data on the efficiency of the ventilation systems are, based on controlled laboratory measurements: Sandberg 1986, Mathisen and Skaaret 1983, Qingyan 1988; or, based on field measurements: Fisk et al. 1988, 1989, 1991, Persily et al. 1985, 1986, 1990, 1991.

AIR CHANGE EFFECTIVENESS AND CONTAMINANT REMOVAL EFFECTIVENESS

The outdoor air requirements or the air change rates listed in existing standards and codes (e.g. ASHRAE 62-89, Table 2) assume perfect mixing of the air in the ventilated space. This assumption does not always apply. It is necessary, therefore to take into account how efficient the air is distributed in the occupied zone. If there are zones of stagnant air and/or short circuiting, it may be necessary to increase the amount of outdoor air. If, on the other hand, there is a displacement flow, the amount of outdoor air may be reduced. To properly assess the ventilation in the breathing zone, one must determine:

- The air renewal/air distribution process: How quickly "old" contaminated air is placed with "new" outdoor air in the occupied zone.
- The contaminant removal process: How quickly generated contaminants are removed, and how effectively the contaminants are prevented from spreading to critical areas, like the occupied zone.

These two processes are related but generally not identicaland therefor need to be treated separately. For both air renewal and contaminant removal it is important to make clear if the results are based on room average, occupied zone average or local conditions. To assess the indoor air quality, the occupied zone average and local conditions must be determined.

The effectiveness of air renewal and contaminant removal are referred to as "air change effectiveness" and "contaminant removal effectiveness" respectively. In the literature there is some confusion regarding these terms. Some publications use air change efficiency or air exchange efficiency to characterize the air renewal/air distribution process. In these publications complete mixing is being referred to as 50% efficiency and complete displacement flow to 100%. In recent standards (ASHRAE 62-89; COST-613 1992) however, perfect mixing is referred to as 100% efficiency. Because an efficiency can not exceed 100% it is recommended to use the word effectiveness. The process of removing contaminants from the space is normally referred to as contaminant removal effectiveness or ventilation effectiveness (COST-613 1992). ASHRAE Standard 62-89 is using the term "ventilation effectiveness" to characterize the air renewal/air distribution process.

Air Change Effectiveness

Air change effectiveness is based on the age-of-air concept (Sandberg 1983; Skaaret 1982; Sutcliffe 1990). The age-of-air in a room is a measure of the time it takes the supply air to reach a given location in the room. Age-of-air can be considered as the local age-of-air, the room or global average age-of-air, and the occupied zone average age-of-air.

The *local age-of-air* is measured at individual points within a room and used if the ventilation at individual work stations, or the distribution of air in naturally ventilated buildings, is to be assessed. It can also be used to map airflows through rooms. The local age-of-air can be determined taking the area between the concentration curve and the final concentration and divide this by the final concentration (equation 1, Table 1). The *room average age-of-air,* measured in the room return air, or *global average age-of-air,* measured in the section return air, quantifies the performance of a ventilation system and can be calculated using equaltion 2 in Table 1 (Sandberg 1983; Sutcliffe 1990). It takes into account both the amount of ventilation air supplied to the room and the efficiency with which this air is distributed in the room. The *occupied zone average age-of-air,* is the mean value of the local age-of-air measured at breathing level at different points in the occupied zone. The air change effectiveness of the ventilation system can be calculated by dividing the local age-of-air in the return by the room average age-of-air.

The air diffusion effectiveness (Fisk et al. 1991) is calculated by dividing the age-of-air at a return grille by the age-of-air at breathing level, measured at a location close to that return grille in the occupied zone. The air diffusion effectiveness is a better indicator of the airflow in the room because it is not influenced by the residence time of air in the plenum and/or the leakage of supply air into the return plenum. The method used to determine the age-of-air in the measurements presented here, was the step-up tracer gas method. This method has been described earlier by Sutcliffe, 1990.

Contaminant Removal Effectiveness

Contaminant removal effectiveness is the effectiveness of the ventilation system to remove contaminants generated in the room. It can be calculated by dividing the contaminant concentration in the extract air (return air from the room) by the average contaminant concentration in the breathing zone. If the contaminant sources are evenly distributed in the room (i.e. building materials, carpet, people) the contaminant removal effectiveness will be similar to the air change effectiveness. This paper only reports measurements of air change effectiveness.

FIELD MEASUREMENTS

The following data were collected from a series of independent field tests. The measurements were part of a general characterization of the indoor climate and the performance of the HVAC systems in the studied buildings. The tracer gas technique was used to measure air flow in ducts, outside air supply, outside short circuiting, infiltration air, and age-of-air. All measurements were done during summer conditions.

The buildings were multi-story served by one or more air handling units. Typically the outdoor air was 10% to 20% of the total supply. All spaces had supply diffusers in the ceiling and returned the air through a ceiling plenum. A short characterization of the test spaces is shown in Table 2 and 3. Each test involved only one section of a building. A section is defined as the total of all spaces covered by one air handling unit and one outdoor air supply. In some of the sections studied the supply duct from the air handling unit branched out to cover different zones. A zone could either be one room (classroom, single office, open plan office floor) or a group of rooms connected to the same return duct. The age-of-air measurement in the return duct after all branches are reconnected, represents the room or global average age-of-air for a section. A schematic of a section in a building is shown in Figure 1.

Test Procedure

A multi point doser and sampler unit (6 points) was used together with a gas monitor. The detection limit for the tracer gas used (SF_6) was 0.005 ppm. Concentrations were monitored in the occupied space, and in the return ducts. In the occupied zone concentrations were measured at breathing level, 1.1 m for sedentary persons, and in some of the tests also at return grilles in the ceiling. During a test the conditions were stable, i.e., amount of outside air, total air flow, and temperature conditions were constant. During occupancy, measurements may have been influenced by opening and closing doors, increased mixing due to body movements, etc..

RESULTS

The results for all buildings are presented in Table 2 and 3. In buildings A, B, C, and D (Table 2) the age-of-air in the return duct represented an entire section. In building F (Table 3) the age-of-air was measured both for the zone and the section. The results for F2 and F3 are from the same open plan office floor measured on two different days in ten different locations at breathing level and corresponding return grilles in the ceiling. The measurements in the returns from the section and the zone were at the same locations both days. The results for F4 were taken at the same locations as F2, but taken during the night when there were no occupants.

The local age-of-air was calculated using equatiion 1 and the average age-of-air for the section and/or zone was calculated using equation 2 in Table 1. The global or zone air change effectiveness, ACE_G and ACE_Z, the occupied zone average air change effectiveness, ACE_{BL}, and the local air change effectiveness, ACE_L, were calculated using respectively equation 3, 4, and 5. The air diffusion effectiveness, ADE, was calculated using equation 6 in Table 1.

The air change rate n, can be calculated as the reciprocal of the age-of-air in the return $1/\tau_N$. For the buildings presented here, the air change rates varied between 0.5 and 3.5 h^{-1}.

DISCUSSION

The average air change effectiveness for the section (ACE_G) and zone (ACE_Z) were in all tests between 0.8 and 1.1. Based on studies and evaluations from Fisk et al. (1991) the 95% confidence limit for these types of measurements are ± 20%. This means that the air distribution in the buildings tested was not significantly different from complete mixing i.e. 1.0. It is generally thought that many systems are unable to distribute the air well and have, therefore, short circuiting of air or zones of stagnant air in the room. The present results on the global air change effectiveness, do not support this, but measurements were only done in the summer season with the systems in the cooling mode, i.e. the supply air temperatures were significant lower than the room temperatures. Other studies have shown (Offermann 1988; Sandberg 1986; Olufsen 1991) that in the winter season, with similar systems in heating mode, i.e. supply temperatures higher than room temperatures, you may find a lower air change effectiveness in the range 0.5 to 0.7.

Although the air change effectiveness for a section/zone shows a value around 1.0, implying complete mixing, this does not necessarily mean that the air distribution in the occupied zone is uniform. To evaluate the distribution of air in the occupied zone, the average age-of-air in the occupied zone $< \tau_{BL} >$ is compared to the age-of-air in the return from the section τ_N. Except for building D, the average air change effectiveness of the occupied zone (ACE_{BL}) varies between 0.8 and 1.2, which is not significantly different from complete mixing, 1.0. The corresponding air change effectiveness measured in building D, ACE_{BL} = 1.4 could be caused by stagnant/slow moving air in the plenum or displacement flow in the room. Unfortunately no age-of-air measurements were made in the return grilles in the ceiling in this building, which would have given an indication why the air change effectiveness of the occupied zone was higher than in the other buildings.

Even an average age-of-air in the occupied zone (ACE_{BL}) of around 1.0 does not necessarily mean perfect mixing. There may still be variation in the age-of-air at the different locations in the occupied zone. This can be evaluated by comparing the local age-of-air measurements at breathing level in the occupied zone τ_{BL} to the age-of-air in the return from the section τ_N. The local air change effectiveness, ACE_L varies significantly in building A (0.7 to 1.2), D (1.0 to 1.8) and F (0.8 to 1.2), which means the air in these buildings is not uniform mixed. In building B (1.1) and C (1.1 to 1.2) the variations are negligible indicating uniform mixing of the air. Since age-of-air at the return grilles in the ceiling was not measured in building A, C and D, the air diffusion effectiveness could not be determined for these buildings. For building B and F the results for the air diffusion effectiveness varied between 0.9 and 1.2, which is similar to the calculated values for the local air change effectiveness, ACE_L, both indicating uniform mixing.

The presented results agree well with measurements reported elsewhere in large office buildings under similar conditions. Fisk et al. (1991) summarized his results from nine different buildings. In these studies the global air change effectiveness, ACE_G varied between 1.0 and 1.4 and the occupied zone average air change effectiveness, ACE_{BL} varies between 0.8 and 1.4. Persily et al. (1985; 1986; 1990; 1991) reported a global air change effectiveness in the range of 0.9 to 1.1.

Although the majority of studies use the age-of-air concept, the question remains which locations represent best the conditions in the space (room average, occupied zone average, breathing level average) and which locations should be used as the reference (return duct from the entire section, return duct from the zone, nearest return grille in the ceiling). Furthermore, because some data are reported assuming perfect mixing to be an effectiveness of 1 or 100%, while others assume perfect mixing to be 0.5 or 50% and complete displacement flow to be 1 or 100%, there is a definite need for guidance and standardization.

CONCLUSION

This paper reported on the field measurements of the air change effectiveness in large commercial buildings during summer (cooling season). In all measurements the tracer gas step-up technique and the age-of-air concept were used. The data indicate that there is limited short circuiting in large buildings operated under summer conditions when the supply air temperature is lower than the room temperature.

The global air change effectiveness, ACE_G, implied perfect mixing but since ACE_G integrates the flow pattern in the entire test space (building) including flow in ducts, flow in ceiling plenums, flow around and in the occupied zone, this is not a good representative of the effectiveness of the distribution of the air in the occupied zone. A better parameter is the occupied zone average air change effectiveness, ACE_{BL}, which is based on age-of-air measurements at breathing level at several locations. But even if this value indicates perfect mixing, there may be locations with stagnant air (effectiveness lower than 1) or locations with displacement flow (effectiveness greater than 1). Therefore, the local air change effectiveness, ACE_L, and/or the air diffusion effectiveness should be evaluated to assess the ventilation at individual work spaces.

Future research should include field measurements taken for different seasonal conditions especially heating periods, and measurements to determine the contaminant removal effectiveness in order to assess the efficiency of contaminant removal. Furthermore, the way of measuring and reporting air change effectiveness should be standardized.

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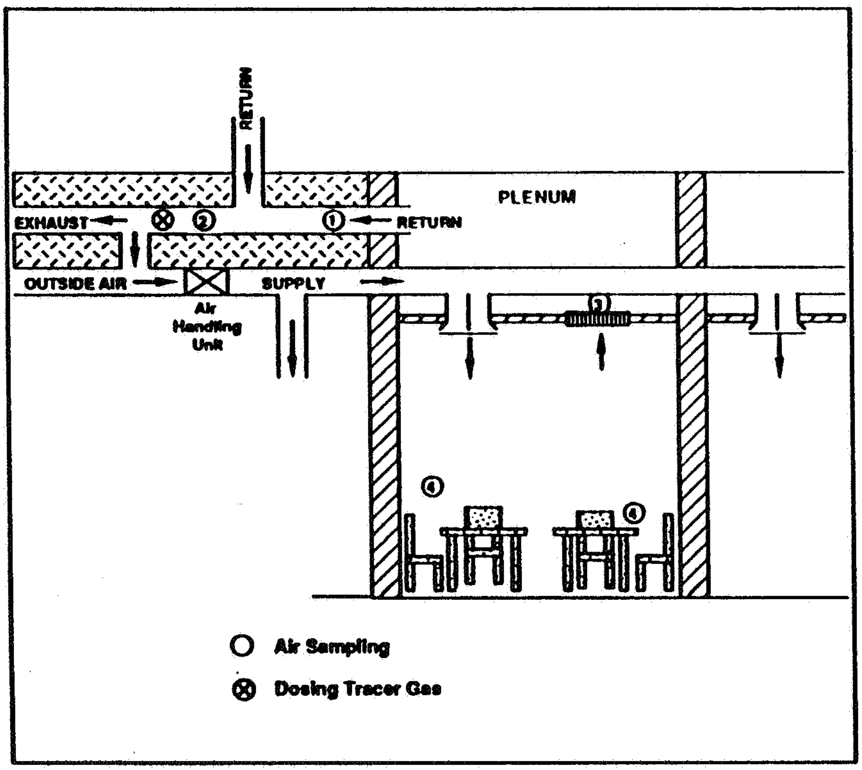

Figure 1. Schematic of a section of a building, showing location of dosing and sampling points in a typical measurement. Sample locations: 1: zone return; 2: section return; 3: grille; 4: breathing level.

#	Parameter	Equation	Unit
1	Local age-of-air	$\tau_p = \int_0^\infty (1 - \frac{C(t)}{C_\infty})\, dt$	h
2	Average age-of-air	$\langle\tau\rangle = \frac{\int_0^\infty (1 - \frac{C_{ex}(t)}{C_\infty})\, t dt}{\int_0^\infty (1 - \frac{C_{ex}(t)}{C_\infty})\, dt}$	h
3	Air Change Effectiveness, global	$ACE_G = \tau_N / \langle \tau \rangle$	
4	Air Change Effectiveness, occ. zone	$ACE_{BL} = \tau_N / \langle \tau_{BL} \rangle$	
5	Air Change Effectiveness, local	$ACE_L = \tau_N / \tau_{BL}$	
6	Air Diffusion Effectiveness	$ADE = \tau_{RG} / \tau_{BL}$	

where
- $C(t)$ = concentration t, ppm
- C_∞ = concentration at time $t = \infty$, ppm
- C_{ex} = concentration in extract, ppm
- t = time, s (h)
- τ_N = local age-of-air in section return
- τ_{BL} = local age-of-air at breathing level
- τ_{RG} = local age-of-air at return grill

Table 1. Equations for calculation of age-of-air and air change effectiveness.

Open office with partitions		Age - of - Air (hours)						Air Change Effectiveness							
		Occ. zone		Return				Average		Local			Occup. zone avg.		
Situa	Ch#	Breathlevel τ_{BL}	$<\tau_{BL}>$	Sec. τ_N	Zone τ_Z	Grill τ_{RG}	Ave. $<\tau>$	Sec. ACE_G	Zone ACE_Z	Sec. ACE_L	Zone ACE_{LZ}	Grill ADE	Sec. ACE_{BL}	Zone ACE_{LZ}	Grill ADE
F2 occupied	1-2	1.75				1.64				0.9	1.0	0.9			
	3-4	1.51				1.47				1.0	1.2	1.0			
	5-6	1.34	1.63			1.33				1.2	1.3	1.0			1.0
	7-8	1.87				1.88				0.8	1.0	1.0			
	9-10	1.69				1.70				0.9	1.0	1.0			
	11			1.56			1.66	1.0					1.0		
	12				1.76		1.72		1.0					1.1	
F3 occupied	1-2	1.98				1.92				0.8	0.9	1.0			
	3-4	1.73				1.64				0.9	1.0	1.0			
	5-6	1.72	1.83			1.55				0.9	1.0	0.9			1.0
	7-8	1.87				1.91				0.8	1.0	1.0			
	9-10	1.83				1.98				0.8	1.0	1.1			
	11			1.51			1.59	1.0							
	12				1.77		1.63		1.1				0.8	1.0	
F4 un-occupied	1-2	1.57				1.81				1.0	1.4	1.2			
	3-4	1.47				1.57				1.0	1.5	1.1			
	5-6	1.34	1.58			1.22				1.1	1.6	0.9			1.1
	7-8	1.82				1.81				0.8	1.2	1.0			
	9-10	1.72				1.91				0.9	1.3	1.1			
	11			1.52			1.61	0.9					1.0		
	12				2.19		2.20		1.0					1.4	

Table 3. Results of age-of-air and air change effectiveness measurements on one floor of an office building.

			Age - of - Air (hours)					Air Change Effectiveness				
Building		Ch#	Occup. zone		Return			Average	Local		Occup. zone avg.	
			Breath.level τ_{BL}	$<\tau_{BL}>$	Sec. τ_N	Grill τ_{RG}	Avg. $<\tau>$	Sec. ACE_G	Sec. ACE_L	Grill ADE	Sec. $<ACE_{BL}>$	Grill $<ADE>$
A	Open office	2	.39						1.2			
	with	3	.54						0.8			
	partitions,	4	.63	.51					0.7		0.9	
	occupied	5	.48						0.9			
		6			.45		.42	1.1				
B	School	1			.50		.48	1.0				
	classroom,	2	.46						1.1	1.1		
	occupied	4-3	.46	.46		.50			1.1	1.1	1.1	1.1
	studyroom, occupied	5-6	.45			.52			1.1	1.2		
C	Single and	1			.71		.85	0.8				
	open office	2	.66						1.1			
	with	3	.65						1.1			
	partitions,	4	.60	.62					1.2		1.1	
	occupied	5	.59						1.2			
	unoccu-	1					1.34	0.8				
	pied situation	2	.98		1.12				1.1			
		3	.91						1.2			
		4	.98	.95					1.1		1.2	
		5	.94						1.2			
D	Office floor	1			.30		.30	1.0				
	and meeting	3	.17						1.8			
	rooms,	4	.18						1.7			
	occupied	5	.20	.21					1.5		1.4	
		6	.31						1.0			

Table 2. Results of age-of-air and air change effectiveness measurements in four different buildings.