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Influence of persons' movements on ventilation effectiveness

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SUMMARY
Most often the ventilation effectiveness of a ventilated room is determined without considering the influence of persons´ movements. Even though the main reason for supplying the ventilation may be to create a healthy and productive environment for the occupants, their own influence on the ventilation is usually disregarded. This paper presents results from a systematic investigation of the movements´ influence on the ventilation effectiveness using human subjects combined with tracer gas measurements. Several typical "movements" are defined and carefully repeated to determine the influence of different kinds of movement compared with the case of no movements. It is found that mixing ventilation is considerably more robust compared with displacement ventilation. At the same time it is found that displacement ventilation on average is more effective than mixing ventilation when movements prevail, even though the movements reduce the effectiveness. Furthermore, it is found that the influence of the different movements vary substantially.

KEYWORDS
Persons' movements, Ventilation effectiveness, Ventilation, Person's activities, Contaminant distribution

INTRODUCTION

During the past two decades awareness of concentration gradients in ventilated rooms has increased and the concept of ventilation effectiveness is widely adopted today (Mundt et al., 2004). Thus, it is a well known fact that for instance personal exposure may depend strongly on the local concentration distribution. Assuming fully mixed conditions may result in substantial errors (Brohus and Nielsen, 1996; Bjørn and Nielsen, 2002).

Most often, however, the ventilation effectiveness of a ventilated room is determined without considering the influence of persons´ movements. Even though the main reason for supplying the ventilation may be to create a healthy and productive environment for the occupants, their own influence on the ventilation due to movements is usually disregarded. The obvious reason is the level of complexity connected with inclusion of movements in the calculations combined with a lack of knowledge from full-scale measurements. Available studies considering persons' movements report a significant influence and strongly encourage the consideration in the design of air distribution and analysis of contaminant distribution (Hillerbrant and Ljungqvist, 1990; Matsumoto et al., 2004; Brohus et al., 2006).

This paper presents results from a systematic investigation of the movements´ influence on the ventilation effectiveness using human subjects combined with tracer gas measurements. A room equipped with selected furniture, heat sources, contaminant sources and a moving person is investigated in case of mixing ventilation and displacement ventilation, respectively. Several typical "movements" are defined and carefully repeated to determine the influence of different kinds of movement compared with the case of no movements.

METHODS

This paper investigates the influence of movements by means of full scale measurements in a ventilated test room using human subjects performing well-defined characteristic movements, see Table 1. Both mixing and displacement ventilation is applied for three different contaminant sources in case of the various movements.

Table 1. Investigated parameters

Parameter	Variation
Ventilation principle	Mixing ventilation Displacement ventilation
Movement (Figure 5)	No movement Five movements
Contaminant source (Figure 4)	At the back (person, warm source) Above Convector 1 (warm source) On Table 1 (passive source)

The test room is shown in Figure 1 and the setup is detailed in Table 2. The test room is built inside a larger test facility.

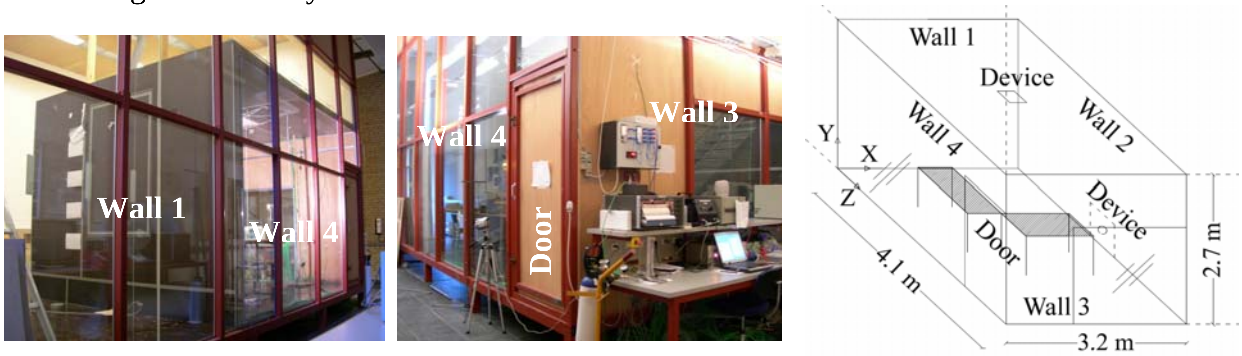

Figure 1. Photos and sketch of the test room.

Table 2. Test room setup

Room volume	35.4 m^3
Air change rate	5 h^{-1}
Location of temperature sensor	Mixing ventilation: In the exhaust duct Displacement ventilation: 1.2 m above floor inside the test room
Temperature set point	21 °C
Operation of the two convectors	Each of 350 W. Applied in case of displacement ventilation only. The purpose is to generate appropriate concentration and temperature stratification.
Stratification height (concentration)	Approximately 1.3 m (only in case of displacement ventilation)

The setup is partly inspired by an operating room which is the reason for the location of the tables and the clothing among others (Brohus et al., 2008), see Figure 2. In case of mixing ventilation the ceiling device is the supply opening and air is exhausted close to the floor. When displacement ventilation is applied the system is somewhat "opposed" with a displacement inlet device mounted at the floor and air exhausted through the ceiling device, see Figure 3. The two convectors are applied only in case of displacement ventilation to generate a proper concentration (and temperature) stratification. One human subject is present all the time standing still or doing the specified movements.

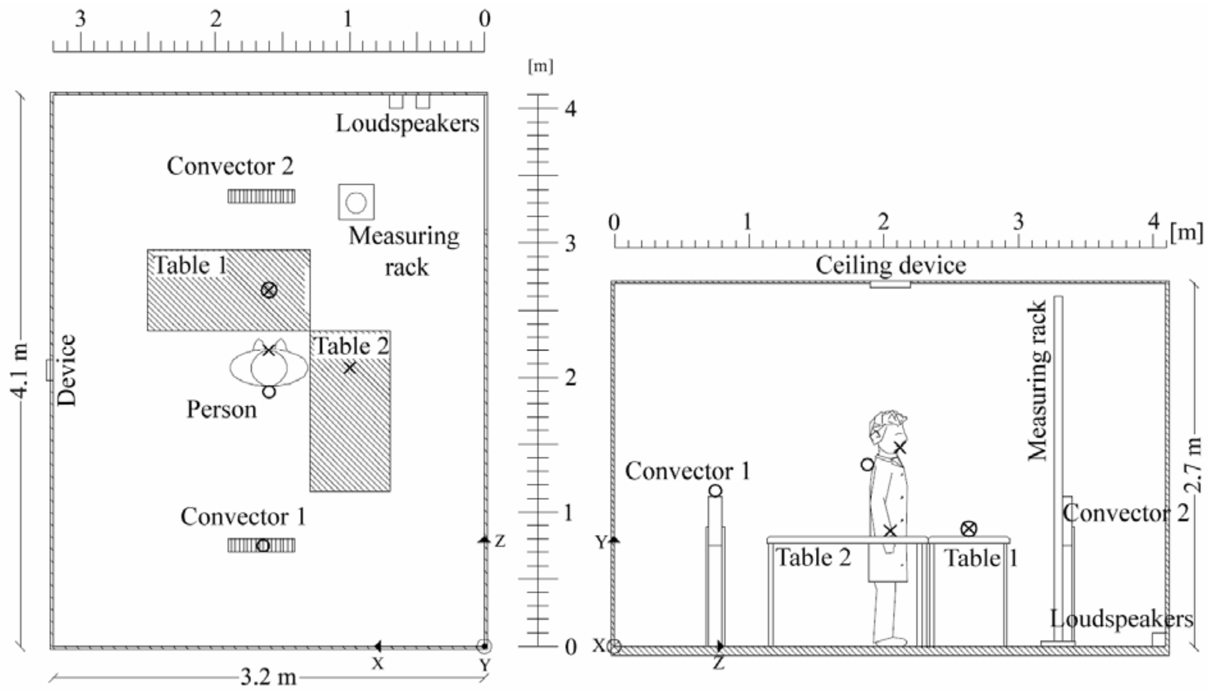

Figure 2. Measurement setup and coordinate system. The circles represent three different contaminant sources (see Figure 4). The crosses represent measurement locations.

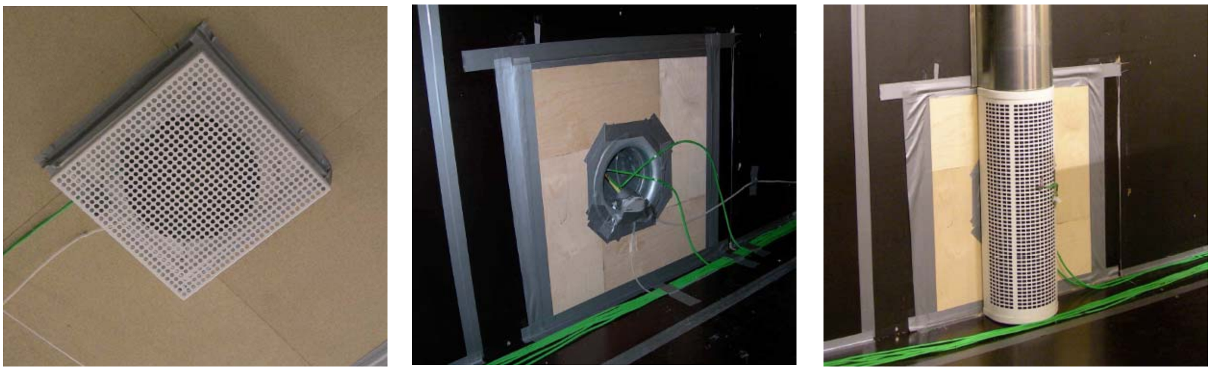

Figure 3. Left: Mixing ventilation inlet device (and exhaust opening in case of displacement ventilation). Centre: Mixing ventilation exhaust opening. Right: Displacement ventilation inlet device.

Figure 4. Three different tracer gas contaminant sources. Left and centre: Source at the back of a person (with and without coat). Upper right: Source on Table 1 (the tracer gas source and the measuring point are not applied at the same time). Lower right: Source above Convector 1.

To investigate the concentration distribution and ventilation effectiveness tracer gas measurements are performed. Three different tracer gas contaminant sources are applied, see Figures 2 and 4, one passive and two "warm" contaminant sources. The passive contaminant source comprises tracer gas supplied on Table 1 and the two warm sources comprise tracer gas supplied at the back of the person under a coat and supplied above Convector 1, respectively. The passive source may represent spread of contaminant locally in front the person. The source at the back may represent bacteria emission, CO_2 or bio effluents. Finally, the source supplied above the heated convector represents a stratified concentration distribution typical for displacement ventilation.

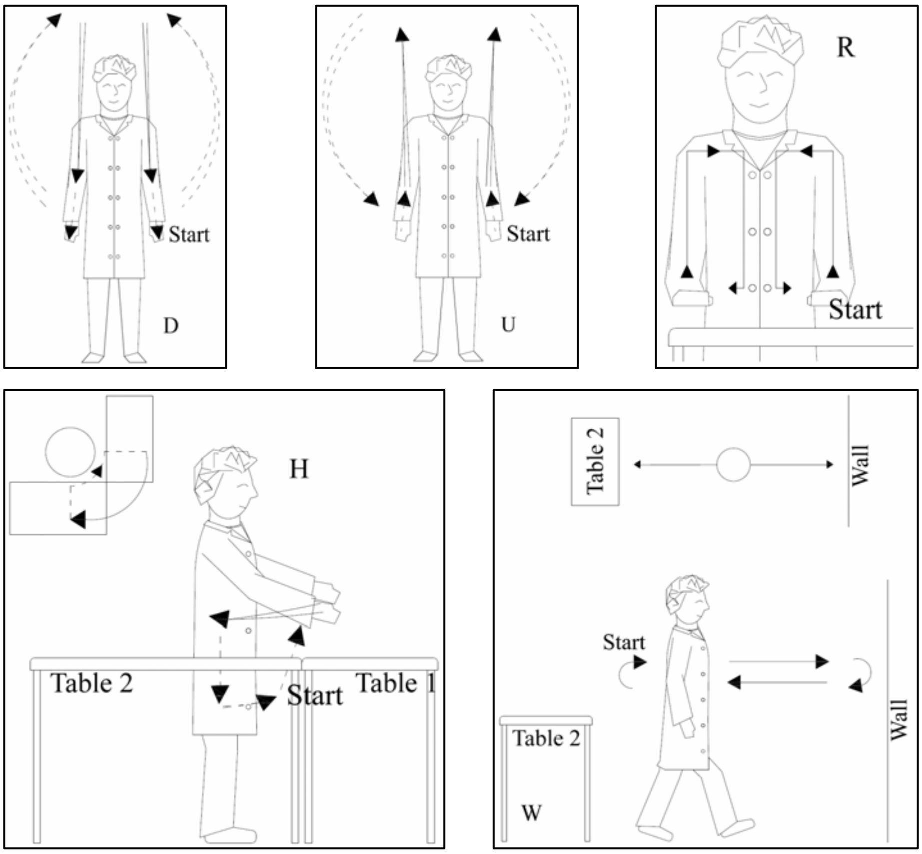

Figure 5. Sketch of five characteristic movements: D = Vertical Downward, U = Vertical Upward, R = Random, H = Horizontal, W = Walking. Full-drawn line means "fast/normal" movement. Broken line means "slow" movement.

The five movements illustrated in Figure 5 include four movements of the arms (feet located at the same place) and one "walking" movement. They are chosen to constitute typical movements inspired by movements that may be found in an operating room and elsewhere (Brohus et al., 2008). On one hand the movements should represent real movements and on the other they should be well-defined and possible to repeat in a systematic and controlled way by the human subject. The speed of the movements is a balance between the speed of the real movements and consideration of the human subject that is going to repeat the movement many times during a measurement series to get enough samples to obtain reliable results. To guide the movements a number of reference points are established in the room together with guiding sound recordings played using the loudspeakers shown in Figure 2.

Table 3 provides information on the specific location of the tracer gas sources and the concentration measurement locations.

Table 3. Measurement setup

Tracer gas source location[1]	
Location (see Figure 4)	Coordinates (*x*, *y*, *z*) in m
At the back Above Convector 1 On Table 1	(1.6, 1.35, 1.935) (1.655, 1.11, 0.8) (1.6, 0.82, 2.65)
Tracer gas concentration measurements[2,3]	
Location	Coordinates (*x*, *y*, *z*) in m
Personal Exposure (*not* when the source is at the back) On Table 1 (*only* when source is at the back) On Table 2 At a height of 1.8 m Exhaust air, in case of mixing ventilation Exhaust air, in case of displacement ventilation	(1.6, 1.55, 2.19) (1.6, 0.82, 2.65) (1.0, 0.82, 2.05) (2.25, 1.8, 3.3) (3.2, 0.3, 2.05) (1.6, 2.7, 2.05)

1: Tracer gas: N_2O
2: Equipment: Brüel & Kjær Multipoint Sampler and Dozer type 1303 and Brüel & Kjær Multigas Monitor type 1302.
3: For each setup concentration is measured at two locations inside the room as well as in the exhaust air. Each setup comprises 40 concentration measurements at each location to ensure reliable results leading to a total duration of 3.5 hours for each case. Steady-state conditions are maintained except – of course – for the systematic movements.

RESULTS

Selected results from the measurements are presented in Table 4 in shape of concentration measurements at four different locations including the personal exposure. Apart from the presented results extensive smoke visualization and various other measurements are performed like concentration and temperature profiles inside the room which are not presented to save space.

Table 4. Selected results from tracer gas measurements

Ventilation	Source[1]	Movement[2]	Exposure[3,4,5]	Table 1	Table 2	H180
Mixing	T	N	1.65 (0.61)		1.12 (0.25)	
	T	U	1.61 (0.83)		1.01 (0.07)	
	T	H	1.56 (0.40)		1.20 (0.52)	
	T	R	1.24 (0.29)		0.95 (0.03)	
	B	N		1.03 (0.04)	0.99 (0.05)	
	B	D		1.05 (0.03)	1.05 (0.07)	
	B	R		1.07 (0.03)	1.07 (0.05)	
Displacement	T	N	0.89 (0.12)		0.38 (0.06)	
	T	H	1.48 (0.31)		1.31 (1.22)	
	T	R	1.29 (0.18)		0.28 (0.03)	
	B	N		0.26 (0.01)	0.31 (0.01)	
	B	D		0.40 (0.08)	0.25 (0.02)	
	B	R		0.43 (0.07)	0.29 (0.05)	
	C	W	0.84 (0.14)		0.47 (0.10)	0.85 (0.10)

1: Tracer gas source (see Table 3): T = On Table 1, B = At the Back, C = Above Convector 1
2: Movements (see Figure 5): N = No movement, D = Vertical Downward, U = Vertical Upward, R = Random, H = Horizontal, W = Walking.
3: Measurement locations are found in Table 3.
4: Dimensionless tracer gas concentration: $c_P^* = c_P/c_R$, where c_P is the local concentration and c_R is the return concentration (i.e. exhaust air).
5: Mean value and standard deviation (in brackets).

All results are presented in terms of dimensionless tracer gas concentration by dividing by the return concentration. The local ventilation effectiveness, and the personal exposure index (Brohus and Nielsen, 1996), can be found by taking the inverse of the results. Thus, a dimensionless concentration of 1 corresponds to fully mixed conditions. Furthermore, levels below 1 correspond to ventilation effectiveness above 1.

DISCUSSION

Influence of movements in case of mixing ventilation

Two contaminant sources are applied for the mixing ventilation case, namely the passive source located on Table 1 and the source at the back of the person, respectively.

First, the source on Table 1 is considered. Here it is evident that the dimensionless personal exposure is above 1 (i.e. ventilation effectiveness somewhat below 1) both in case of no movements and for the three chosen movements. The corresponding results regarding the concentration on Table 2 indicate a level much closer to 1, however, depending on the kind of movement. It is clear that the contaminant source in front of the person is partly entrained in the convective boundary layer along the person and transported to the breathing zone, a fact which is supported by smoke visualisation.

The "random" movement seems to generate the highest level of local mixing and produces the lowest concentration at both locations. The "horizontal" movement is found to transport lumps of fluid containing tracer gas from the source area above Table 1 to the measuring location on Table 2. Thus, even though the air change rate is reasonably high (5 h^{-1}) the mixing ventilation may be quite sensitive to local passive sources.

Second, the heated source (tracer supplied at the back of the person) is examined. The measurements on Table 1 and Table 2 show levels quite close to 1 for all movements indicating that the mixing is effective in this case.

Influence of movements in case of displacement ventilation

In case of displacement ventilation the difference between the passive and the warm source is pronounced and the influence of movements is highly significant.

Compared with mixing ventilation the stratified concentration distribution in the displacement ventilation case reduces the exposure due to entrainment of clean air from the lower cleaner part of the room when the persons is standing still. In case of movements the results look more like the mixing ventilation case due to the local disturbances in front of the person caused by the movements. The concentration on Table 2 is clearly influenced by the movements. When "no" and "random" movements occur levels below 0.4 prevail whereas "horizontal" movements generate a level exceeding 1 which is even worse than the mixing case.

When the source is located at the back the concentrations on Table 1 and Table 2 are quite low for "no", "downward" and "random" movements. Especially in case of no movement very high ventilation effectiveness is found (1/0.26 = 3.8). In this case the displacement principle is much more robust than in case of the abovementioned passive source.

The "walking" movement is investigated using another heated source in shape of tracer gas released above the heated Convector 1 (see Figure 4). In this case the contaminant is transported to the upper part of the room generating a clearly stratified flow. Here it is seen that the personal exposure equals the concentration approximately at the same height measured at a “neutral” part of the room without local influence from the walking person. This result corresponds well with the findings of Brohus and Nielsen (1996). The concentration on Table 2 is significantly lower, around half the exposure level, which indicates that significant stratification prevails despite the substantial local disturbances caused by the “walking” movement.

Mixing ventilation vs. displacement ventilation

When mixing ventilation and displacement ventilation are compared the result is highly dependent on the kind of contaminant source. If the source is warm it is found that the ventilation effectiveness of displacement ventilation is significantly higher (approximately 2 – 4 times) than mixing ventilation almost irrespective of the movements in the present case.

The only movement in the displacement ventilated room that results in “mixing-like” ventilation effectiveness is “walking” which is also expected. Here, it should be noted that the stratification height is around 1.3 m, i.e. below breathing zone height. If the stratification height was found above breathing zone height it would presumably result in higher ventilation effectiveness, however, at the expense of substantially increased air flow rate and energy consumption.

When the influence of the passive contaminant source is investigated the outcome is quite different. On average the displacement ventilation still provides the lowest exposure as well as Table 2 concentration even though the difference is substantially reduced. However, now the displacement principle is less robust and may in certain cases cause higher local concentrations than in the mixing case. This may be due to the fact that significant stratification may “catch” and lock amounts of contaminant in a horizontal layer (as found by Bjørn and Nielsen (2002) among others).

This indicates that displacement ventilation may be excellent in offices, where the main pollution sources are warm, whereas it cannot be recommended in hospitals where high local bacteria concentrations may jeopardize the hygiene.

Thus, overall it can be stated for the present test case that displacement ventilation has higher ventilation effectiveness that mixing ventilation. However, displacement ventilation is less robust to the influence of movements.

CONCLUSIONS

It is found that mixing ventilation is considerably more robust compared with displacement ventilation. At the same time it is found that displacement ventilation on average is more effective than mixing ventilation when movements prevail, even though the movements reduce the effectiveness. Furthermore, it is found that the influence of the different movements vary substantially. In general ignorance of the influence of persons’ movements may lead to significant overestimation of the ventilation effectiveness as well as an overestimation of the robustness of the air distribution system.

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