The Impact of Surface Air Movement on Material Emissions

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The effects of surface air movement on material emissions were investigated experimentally. A field study was carried out to understand the characteristics of surface air movement in real rooms, and a velocity-controlled test chamber was designed and built, based on the field study results, to provide a uniform mean air flow and boundary layer condition over the test area. An extensive experimental study on the effects of air movement on material emissions was carried out, under different mean flow velocities and turbulence fluctuations, by using the small velocity-controlled test chamber. It was found that material emission rates are a function of the surface air flow conditions: as surface air velocity increases, contaminants from materials deplete faster; the turbulent fluctuation has a lesser effect on material emissions. © 1997 *Published by Elsevier Science Ltd.*

INTRODUCTION

Building materials have been identified as major sources of indoor contaminants and their emission rates are effected not only by the vaporizable constituents and their distribution, but also by humidity, surface velocity, temperature and material loading factors [1–3].

Material emissions are the results of several mass transport processes. The interaction of these processes commonly occurs, and their effects on material emissions are somewhat complex. However, the emissions can be considered to stem from two main processes: diffusion of a compound through a material as result of a concentration, pressure, temperature or density gradient, and the surface emissions occurring between the material and the overlying air as a consequence of several mechanisms, such as evaporation, convection and diffusion. In wet materials, the evaporation of a compound is a dominating process, and therefore, the vapour pressures of the compound and overlying air can be shown to be proportional to their concentrations. The mass transfer coefficient is dependent upon the environment in which these processes are taking place, including the air temperature, relative humidity, surface air velocity, turbulence fluctuation, and surface characteristics. Even though the principles of mass transfer and evaporation processes are well established in the literature [3], very little information exists related to material emission processes. De Bellis *et al.* [4] studied the influence of room air temperature and relative humidity on emission rates from paint and varnish. They noticed that as the temperature increased, the Total Volatile Organic Compounds (TVOC) concentrations and emission rates increased for both the paint and varnish. However, the individual compounds did not necessarily follow the same trend established by the TVOC.

Although the importance of air velocity on the emission rate of indoor sources has been highlighted in recent studies of chamber testing methods, little systematic work has been done to study the influence of surface air movement on the material emission rate. Knudsen *et al.* [5] identified that surface air movement has a non-negligible effect on material emissions. Iwashita *et al.* [6] studied the effect of surface air velocity on material emissions using sensory evaluation methods. At times, results obtained by different researchers are contradictory [7–9], and with experimental procedures and facilities varying extensively, it is difficult to draw definite and conclusive answers to the effects of surface air movement on material emissions. The studies carried out thus far were qualitative studies since the surface air movement was not controlled, and quite a few of them were sensory studies. As stated in the current ASTM D5116 section 4.2.4.3 [10], "an understanding of the effect of velocity on the emission rates is needed in interpreting small chamber emission data".

The present paper reports the results of a series of experimental tests carried out to investigate the relationship between the surface air movement (velocity and turbulence fluctuation) and material emissions.

DESIGN AND SET-UP OF EXPERIMENTAL FACILITY

To conduct an experimental study of material emissions in a test chamber with real indoor environmental conditions, the characteristics of surface air flow in the indoor environment must be understood first. Several field studies of air flow characteristics in the occupied zone have been reported. Most of these studies are for thermal comfort purposes and the measurements were

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Table 1. TMain characteristics of the investigated spaces

Space no.	Heating system	Type of space	Space volume (m³)	Floor area (m²)
1	Electrical base-board heating	Bedroom	33.6	12
2	Convector beneath window	Bedroom	50.5	20.2
3	Ceiling HVAC	Office	88.75	35.5
4	Convector beneath window	Living room	91.15	36.5

Table 2. The measured velocities and RMS

No.	Distance from surface (mm)	Velocity			RMS (m/s)		
		Low	Mean	Median	Low–high	Mean	Median
1	8	0–0.29	0.0645	0.0508	0.01–0.18	0.032	0.273
	4	0–0.36	0.0757	0.0697	0.02–0.21	0.094	0.0283
2	8	0–0.06	0.0141	0.00318	0–0.05	0.022	0.0173
	4	0–0.04	0.0093	0.00575	0–0.04	0.031	0.0305
3	8	0–0.025	0.109	0.118	0–0.07	0.071	0.082
	4	0–0.18	0.0460	0.040	0–0.09	0.038	0.037
4	8	0–0.19	0.0601	0.0647	0–0.10	0.036	0.034
	4	0–0.11	0.0655	0.0682	0–0.09	0.029	0.0223
Average			0.0555	0.0526		0.044	0.0348

taken in the thermal occupied zone, which is typically at distances of 0.6–1.4 m from the floor, 0.3–1.2 m from the nearest wall, and at least 2 m away from ventilation system outlets [11, 12].

A series of field measurements was carried out to obtain information about the actual surface air velocity and turbulence fluctuation (near walls and floors) in a real room. The field measurements were performed in four different types of heated or ventilated, furnished spaces in Montreal, Canada during the winter season. The main characteristics of the investigated spaces are shown in Table 1.

In each space, air velocity and turbulent fluctuation were measured in at least six locations. One location was at a height of 0.6 m from the floor in the centre of the room, the rest were located near the floor or walls at a height of 0.6 m from the floor. An Indoor Climate Analyzer, manufactured by Bruel and Kjaer (Type 1213), was used to measure the surface air velocity and turbulent fluctuation. The measurements were taken at 4 and 8 mm from the surfaces. All the locations were chosen away from the heating or ventilation systems. The measurements were taken every 6 minutes for a period of 6 hours in a space with no occupancy or with the presence of a sedentary person.

More than 5000 readings were recorded. Values less than 0.01 m/s were taken as 0 due to the instrument's detection limit (0.01 m/s). Table 2 shows the results of air velocity and turbulent fluctuation measured from the four spaces. The turbulent fluctuation is expressed by the Root Mean Square (RMS) of instantaneous velocity (v), i.e. $(\sum(v^2)^{1/2})/t$, where t is time. Because the air velocity and turbulent fluctuation have large variations, the lowest and highest value, mean and median values are reported. As can be seen, the surface velocity can reach values as high as 0.36 m/s in one of the investigated spaces. The measurement value is the mean over

6 minutes, therefore velocity higher than 0.36 m/s may occur over a shorter interval. The majority of the velocity values measured are less than 0.1 m/s, therefore the mean and median values are approximately 0.0555 and 0.0526 m/s, respectively. The turbulent fluctuation, presented as RMS, has a highest value of 0.21 m/s, with mean and median values at 0.0448 and 0.0348 m/s, respectively.

An air velocity-controlled test chamber was designed to provide a uniform air flow pattern and boundary layer condition over the test area, at velocity and turbulence ranges occurring in real rooms. The test chamber is made of stainless steel and consists of two parts: a rectangular chamber area with an indented test area and a cone shaped part as shown in Fig. 1. At the junction of these two parts, there are two fans installed to draw air through the test chamber. Mean air velocity and turbulent fluctuation in the chamber can be changed independently and intermittently [13].

Temperature and humidity control of the chamber and its inlet air is achieved by placing the chamber in an air-conditioned room with an exhaust hood. The temperature and humidity of the room is controlled by the
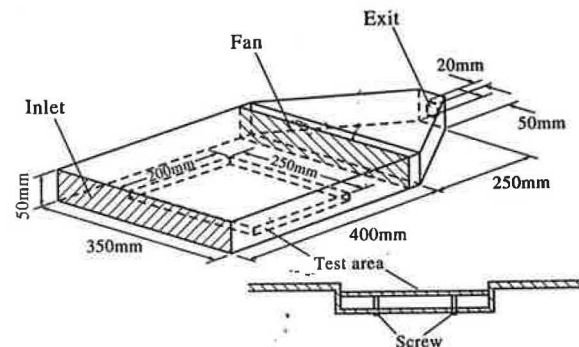

Fig. 1. The small air velocity controlled test chamber designed at CBS.

Table 3. Experimental conditions of each run

Material	Weight (g)	Mean velocity (m/s)	Turbulent fluctuation (m/s)
Varnish	12.66	0.053	0.0025
	12.80	0.114	0.0034
	12.75	0.053	0.0094
	12.62	0.114	0.0114
	12.65	0.114	0.0114
Paint	26.53	0.053	0.0025
	27.24	0.114	0.0034
	26.70	0.114	0.0114
	27.20	0.114	0.0114

Table 4. Major organic compounds identified via GC/MS

Material	Organic compounds identified
Paint	ethylbenzene, hexanal, 2-methyl-3-*h*-propanic acid *m* + *p*-xylene, toluene, 1,2,4-trimethylbenzene
Varnish	butanone, ethylbenzene, dimethylbenzene, *n*-decane, nonane, 1,3,5-triethylbenzene

diphenyl and 95% dimethylpolysiloxane. The oven temperature was programmed to an initial temperature of 10°C for two minutes, followed by a ramp step of 4°C/minute to 200°C, then followed by a second ramp step of 25°C/minute up to 250°C, which was maintained for 5 minutes. TVOC was quantified by using toluene as the reference compound.

Prior to each run, the chamber was cleaned with an alkaline detergent (as recommended by the ASTM Guideline D-5116-90) and flushed with room air for 24 hours before placing the sample into it. A sample of chamber air was taken and analysed by the GC/FID to ensure the air was clean. Prior to use, the breakthrough limits of the multisorbent tubes used for sampling were checked with sampling backup tubes and the conditioned tubes were examined on the GC/FID to ensure the tubes were clean.

A thin PMMA plate, with sample test area of 224.6 × 174.6 mm and dimensions of 250 × 200 × 10 mm, was used as the substrate. To save the lengthy and troublesome cleaning process after each test, a polyethylene wrap, containing no plasticizers, served as a protective cover over the plastic plate. The wrap was tested for emissions and yielded nothing.

First, the substrate with the cover was placed on a balance in order to obtain the intended weight of sample; the intended amount of paint or varnish was poured into the substrate, and was distributed evenly with a stir stick. The painted samples were placed at the intended test area on the bottom of the chamber shortly (less than 5 minutes) after the varnish or paint was applied. The test started as soon as the sample was put into the chamber, which was set at the required flow condition listed in Table 3.

The organic concentrations in the air exiting from the chamber were collected by adsorption on the multisorbent tubes. The time interval between sampling and sampling volumes increased as the chamber VOC concentration decreased. The duration of each experiment was approximately 1 week, and 20 VOC samples were taken during the test periods. Immediately following each test, the sample was weighed again to obtain the amount lost during the experiments. The VOC samples were thermally desorbed and analysed by the GC/FID. All testing was conducted at 23°C and 50% RH.

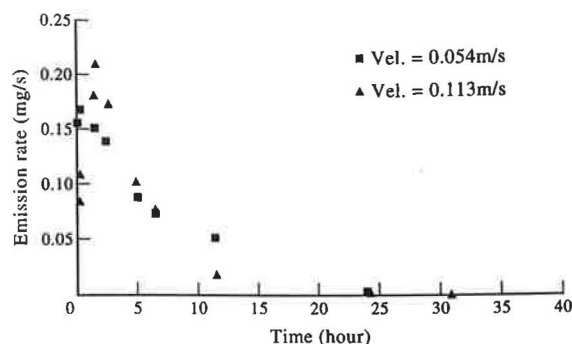*Experimental results.* Table 4 shows major organic

Fig. 4. Varnish emission rates vs time at two surface air velocities when turbulent fluctuation (RMS) is 0.003 m/s.

compounds identified by headspace analysis for the paint and varnish.

As discussed earlier, surface air movement affects material emission rates. Figures 4 and 5 show the emission rates of total VOCs from varnish over time for two different surface air velocities. Note that the emission rates decrease rapidly with time during the first few hours. The emission rates are initially higher for the higher surface air velocity ($v = 0.113$ m/s); after 10–15 hours, the rates are higher for the low surface air velocity ($v = 0.054$ m/s). Thus, the higher surface air velocity caused the material emission source to deplete faster. This is consistent with the flow boundary layer theory and by mass conservation theory.

Figures 6 and 7 show the emission rates of total VOCs from varnish over time for two different surface turbulent fluctuation levels. Note that the effects of turbulent fluctuation levels on material emission rates are smaller compared to that of surface air velocity; and unlike surface air velocity, the turbulent fluctuation levels and material emission rates have an inversely proportional relationship.
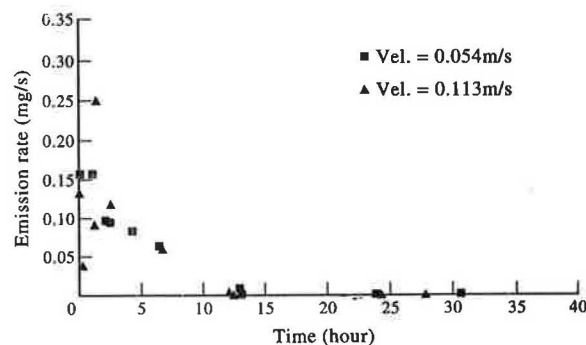

Fig. 5. Varnish emission rates vs time at two surface air velocities when turbulent fluctuation (RMS) is 0.0114 m/s.
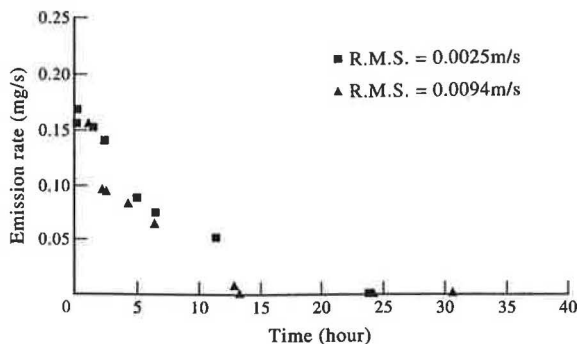
Fig. 6. Varnish emission rates vs time at two turbulent fluctuation levels when surface air velocity is 0.054 m/s.
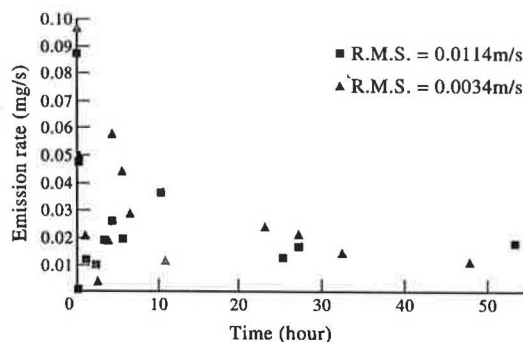

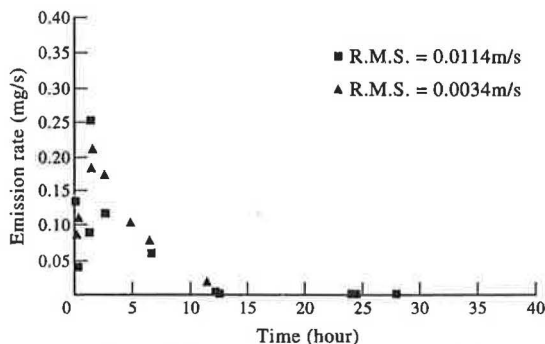Fig. 7. Varnish emission rates vs time at two turbulent fluctuation levels when surface air velocity is 0.114 m/s.
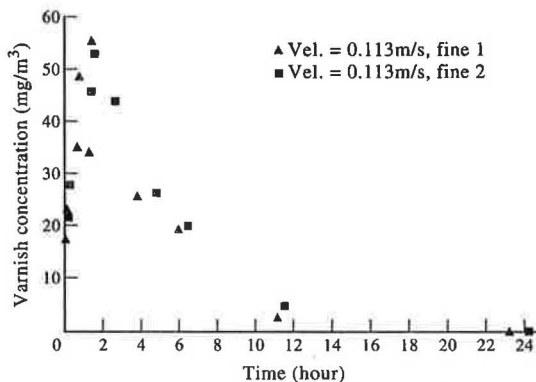

Fig. 8. Acrylic paint emission rates vs time at two surface air velocities when turbulent fluctuation (RMS) is 0.003 m/s.

Fig. 9. Acrylic paint emission rates vs time at two turbulent fluctuation levels when surface air velocity is 0.114 m/s.
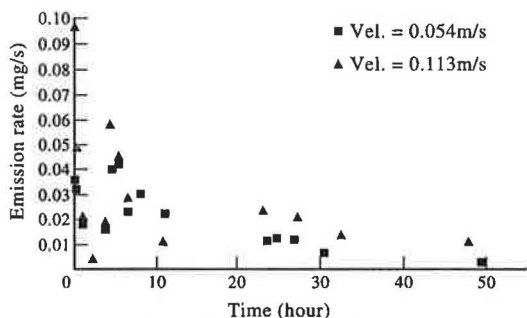

Fig. 10. Two identical varnish test results.

The experimental results of the emission rates of total VOCs from acrylic paint versus time at two different velocities are shown in Fig. 8. It shows that the paint emission rates and their decay rates during the initial stage are much smaller than that of varnish; and the emission rates remain higher for the higher surface air velocity ($v = 0.113$ m/s) during the 50 hour experimental period.

Figure 9 shows the emission rates of total VOCs from paint over time for two different surface turbulent fluctuation levels. The curves of emission rates fluctuate and the effects of turbulent fluctuation on emissions are not obvious due to its weaker effect on boundary layer shear stress, hence the emission rates.

The different behaviour of the VOC emissions from paint and the varnish may be due to the high water content and the relatively low content of VOCs in the paint. Firstly, the release of water vapour from the paint sample impedes the early release of VOCs because the water prevents the VOCs in the paint sample from being released due to hydrogen bonding. Secondly, the humidity affects the efficiency and accuracy of the sampling techniques because charcoal and ambersorb in the sorbent tubes absorb water, consequently, their ability to adsorb VOCs changes.

Replicate tests were carried out for the varnish. The typical results are shown in Fig. 10. It can be seen that the deviation between the two identical tests is quite small, which means the tests have a good repeatability.

CONCLUSION

In the process of the experimental study of surface air movement effects on material emissions, air flow characteristics in real rooms were measured. It was found that the surface air velocities in the test rooms are in the range of 0–0.36 m/s and the turbulent fluctuations, expressed as R.M.S., are in the range of 0–0.21 m/s, with mean and median values of 0.0448 and 0.0348 m/s, respectively. Based on the above information, a small velocity-controlled test chamber was built in order to experimentally study the relationship between material emission rates and surface air movement.

The first quantitative study of surface air flow effects on material emission rates was carried out in the velocity-controlled test chamber. Three materials (water, paint

and varnish) were tested. The results confirm that the surface air flow condition does effect material emissions. They indicate that, for a constant source, material emission rates increase as the air velocity increases; for wet materials, material emission rates are higher during the initial period of testing at the higher surface velocity, and become lower near the end. The effects of turbulent fluctuation on material emission rates are weaker compared to the effects of surface air velocity.

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