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Improving the indoor air quality by using a surface emissions trap

Pawel Markowicz, Lennart Larsson*

Lund University, Department of Laboratory Medicine, Division of Medical Microbiology, Sölvegatan 23, SE-22362 Lund, Sweden

HIGHLIGHTS

- A surface emissions trap reduced moisture-driven emissions from PVC flooring.
- The device decreased significantly the perceived odor from a chemicals mixture.
- RH and temperature did not affect the product's performance.
- Accelerated aging simulating 10 years device lifetime did not affect its performance.
- The device may represent a new tool for improving the indoor air quality.

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ABSTRACT

The surface emissions trap, an adsorption cloth developed for reducing emissions of volatile organic compounds and particulate matter from surfaces while allowing evaporation of moisture, was used to improve the indoor air quality of a school building with elevated air concentrations of 2-ethyl-1-hexanol. An improvement of the perceived air quality was noticed a few days after the device had been attached on the PVC flooring. In parallel, decreased air concentrations of 2-ethyl-1-hexanol were found as well as a linear increase of the amounts of the same compound adsorbed on the installed cloth as observed up to 13 months after installation. Laboratory studies revealed that the performance of the device is not affected by differences in RH (35–85%), temperature (30–40 °C) or by accelerated aging simulating up to 10 years product lifetime, and, from a blinded exposure test, that the device efficiently blocks chemical odors. This study suggests that the device may represent a fast and efficient means of restoring the indoor air quality in a building e.g. after water damage leading to irritating and potentially harmful emissions from building material surfaces indoors.

1. Introduction

Unsatisfactory indoor air quality can result from emissions of particulate matter (PM) (Rohr and Wyzga, 2012), volatile organic compounds (VOCs), or gases like radon, from the materials in a building (Nicolas et al., 2007; Uhde and Salthammer, 2007). Such emissions may be due to building dampness and may seriously affect human wellbeing and health (Bernstein et al., 2008; Sahlberg et al., 2013; Tuomainen et al., 2004). Rudblad et al. (2002) showed that long-term exposure to emissions from damp school buildings triggers hyperreactivity of the upper airways, whereas Mendell et al. (2011), in a comprehensive review, reported evidence of associations between building dampness and asthma.

A wide range of devices for removing both particulate and gaseous pollutants indoors are commercially available (Zhang et al., 2011). PM can be removed by using for example mechanical HEPA (high efficiency particulate) air filters or powered electronic air cleaners (e.g. ionizers). Filters tend to quickly lose efficiency, for example when blocked by dust or when sorbents become saturated, and require regular maintenance (Fisk et al., 2002; Sublett et al., 2010). VOCs can be removed or/and diluted by using activated carbon filters, photocatalytic oxidation (PCO) cleaners or ozone generators. However, PCO cleaners (Kolarik and Wargocki, 2010) as well as ozone generators (Weschler, 2006; Wolkoff et al., 2000) may at the same time increase the concentrations of some other VOCs including potential lung irritants such as formaldehyde. Poor ventilation may lead to increased humidity and accumulation e.g. of VOCs or organic allergens (Clausen, 2004; Weschler, 2004). In some cases, emissions from the building can be avoided by replacing damaged materials with new ones. If the emissions are moisture-related it is important also to take measures for

* Corresponding author.
E-mail address: lennart.larsson@med.lu.se (L. Larsson).

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preventing further water intrusion (Haverinen-Shaughnessy et al., 2008). Replacing building materials may be inconvenient mainly due to emissions formed from moisture-driven degradation of glue used to attach a plastic carpet on a concrete floor. Such emissions are known to diffuse several centimeters into the concrete (Tuomainen et al., 2004). Installing a ventilated floor or a tight polymer is commonly recommended in such cases.

Recently a new device, the surface emissions trap, was developed for reducing emissions from building material surfaces indoors e.g. following a water damage, the goal being to prevent such emissions from reaching individuals residing inside the building. The device is a laminate with two protective sheets of nonwoven polyester fabric surrounding an adsorption layer and a hydrophilic polymer sheet. The device traps only emissions coming from the surface to which it is applied. The function of the polymer is to prevent emissions from the outside to come in contact with the adsorbent layer (Markowicz and Larsson, 2012). We described previously (Markowicz and Larsson, 2012) some of the characteristics of a material prototype in laboratory experiments. Emissions of VOCs were reduced by on average 98%, particle-bound emissions such as mycotoxins were blocked, and the water vapor resistance was 200 s/m, a very low value. The aim of the present investigation was to test the ability of a device prototype to improve the air quality in real environmental conditions (i.e. in a water-damaged school building) by reducing emissions from the floor.

2. Materials and methods

2.1. Case study building

A school built in the 1970s, with a long history of complaints on air quality among the pupils and the school staff, was studied. Increased ventilation and use of air purifiers in the rooms had not resulted in any major improvements in the perceived air quality. A surface emissions trap prototype (cTrap Ltd., Lund, Sweden) was attached on the existing PVC flooring, by using a double sided adhesive tape, in a small office room (room A, 9 m^2). The material, a laminate with one adsorption and one polymer layer, adsorbs only from the adsorption layer side; hence the device was applied with the adsorption layer facing the floor. Thereafter the device was installed in a class room (room B, 30 m^2); over the device was laid a laminate flooring. Because of the unsatisfactory perceived air quality, room B was not in use since several months. The ventilation in both rooms was 2–2.5 air exchanges per hour as measured by the HVAC system. Air samples as well as samples of the surface emissions trap cloth were taken from the floor (immediately replaced with new pieces of the device) at different time periods for measuring the amounts of 2-ethyl-1-hexanol in the air and adsorbed on the cloth, respectively. 2-Ethyl-1-hexanol, a moisture-induced decomposition product of compounds in floor glue and/or of plasticizers in the PVC flooring (Sjöberg and Ramnäs, 2007; Uhde and Salthammer, 2007), was the dominating VOC found in air samplings taken before the device was installed. Tenax TA tubes were used for passive air samplings, as recommended by Sunesson et al. (2002), for 1 week and sent to IVL (Stockholm, Sweden) for thermal desorption and gas chromatography–mass spectrometry (GC–MS) analysis. The cloth pieces (approximately 3 cm^2, $n = 4$) were extracted by using dichloromethane following GC–MS (Markowicz and Larsson, 2012). Material was also collected from the surface of the device ($n = 3$), laminated flooring ($n = 2$), and PVC flooring ($n = 2$) by using an adhesive tape 13 months after the surface emissions trap had been applied in room B, and sent to IVL (Stockholm, Sweden) for mold microscopy. After the installation several of the staff reported that the unpleasant smell had disappeared, and another 470 m^2 of the material was installed in the school building directly on the PVC flooring and subsequently covered by a laminate flooring.

A series of studies on the performance of the device relevant for evaluating its usefulness in improving the air quality of buildings following water damage such as the studied school, including floor emissions measurements, the effects of relative humidity (RH), temperature, and accelerated aging, were conducted as described below.

2.2. Field study of floor emissions

The efficiency of the surface emissions trap in reducing floor emissions was studied (by FuktCom, Lund, Sweden) in a storage room with a PVC flooring. FLEC measurements had previously revealed distinct amounts of n-butanol, 2-ethyl-1-hexanol, and 2,2,4-trimethyl-1,3-pentanediol diisobutyrate (TXIB) being emitted from the flooring.

Two identical devices consisting of 1-L glass desiccator lids with two sampling holes were applied on the flooring either covered or uncovered by the material. By using an adhesive tape (Tesa® 4195 PV2) an aluminum foil was attached on the edges of the desiccator lids in such a way that it covered the flooring surrounding the experiment devices. Air samples were taken three months after the application of the devices. In brief, air was pumped through Tenax TA tubes for 30 min at 100 ml/min, which were then sent to IVL (Stockholm, Sweden) for analysis.

2.3. Human perception of VOCs reduction

Seven months after 500 sqm of the device had been installed in the school, a form was handed out to each of the 24 school teachers where they were asked to answer whether the installation had any effects on the perceived air quality.

An experiment was conducted where 15 male healthy medical-student volunteers (nonsmokers), in ages between 21 and 25 years, were asked to describe how they individually perceived the odor from an aqueous mixture of 11 VOCs (purchased from Sigma Aldrich, Schnelldorf, Germany) in a vessel covered or not covered by the device. Women were excluded from the study to avoid any potential adverse effect on a fetus. The VOCs used were 1-butanol (1940 ppm), 3-methyl-2-butanol (250 ppm), dimethyl disulfide (500 ppm), styrene (1400 ppm), anisole (1250 ppm), alpha-pinene (260 ppm), 1-octen-3-ol (1050 ppm), 2-ethyl-1-hexanol (1350 ppm), toluene (1350), geosmine (0.03 ppm, in a mixture with 2-methylisoborneol), and phenol (150 ppm). The VOCs were mixed in distilled water with a few droplets of a detergent (Tween 80, purchased from MP Biomedicals, LLC Solon, USA) and the mixture was transferred into 15-ml vials which were then sealed with caps and stored until the experiment started 2–3 h later. Three minutes before each participant started to sniff a vial was uncapped and the content transferred to a glass Petri dish and placed in a plastic container (300 × 200 × H6.5 mm, 2.6-L). The container was immediately sealed with a lid with a 15 × 3 cm slit which was covered either by the two nonwoven non-functional material layers taken from the device or by the device (the "control" and the "device" group, respectively, see below). By visual inspection it was not possible to distinguish the two nonwoven non-functional material layers from the material. Each participant was asked to sniff, for about 3 s, the air immediately above one of the boxes placed in a ventilating hood. Thereafter the participant was asked to fill in a simple questionnaire on his perception of the odor intensity (see below).

The volunteers had been randomly assigned to the "control" or "device" group (resulting in 7 subjects for the "control" and 8 for the "device"). A coin flip decided that "A" labeled "device" and "B"

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labeled "control". The random assignment used the R language and system for statistical programming (R Development Core Team, 2012). The null hypothesis states that the difference between the "control" and "device" is zero, and the one-sided alternative hypothesis states that the "device" has a lower response. The null-hypothesis was rejected in favor of the alternative hypothesis that the material reduces the odor. Zhang et al. used a 0–8 point intensity odor scale (Zhang et al., 2002b) where the odor intensity of n-butanol decreased linearly with the dilution on a log scale. Our aim was to use such concentrations of the chemicals that the "control" responses would be placed in the intensity range between 5 and 8 (mean) whereas the "device" responses would be placed between 0 and 1 (mean). Exposing subjects to the combination of chemicals allowed a test of the hypothesis that the surface emissions trap was effective in protecting against multiple contaminants. In the present study the integer scores were given from 0 to 80, in multiples of 10 (rather than 0–8), and each participant was directed to circle the response that best described the smell. The labels were provided to the bilingual subjects in both English and Swedish. A follow-up question requested that they would specify a numerical answer from the continuum of 0–80. This use of a follow-up question follows guidelines of survey researchers (Groves et al., 2009). The experiment was approved by the Regional Ethical Committee in Lund, Sweden.

2.4. Impact of RH and temperature

The impact of RH and temperature on the ability of the surface emissions trap to reduce air concentrations of VOCs was studied. 20 ml each of two aqueous solutions (Solution 1, containing 8 different VOCs and Solution 2, containing 12 different VOCs) were transferred into separate glass Petri dishes. The test VOCs were selected as a model of emissions, representing compounds which are commonly found in indoor air of water-damaged buildings and belonging to different classes of chemicals of relatively smaller (Solution 1) and larger (Solution 2) molecular weight. Solution 1 contained acetone (13.8 μM), 2-methyl-1-propanol (14.8 μM), benzene (12.8 μM), ethyl acetate (11.3 μM), 2-methylfuran (13.4 μM), 1-propanol (18.3 μM), 1-methoxy-2-propanol (13.3 μM), and ethanol (13 μM). Solution 2 contained 1-butanol (42 μM), 3-methyl-2-butanol (82 μM), 3-methylbutanol (13 μM), dimethyl disulfide (17 μM), hexanal (42 μM), 2-heptanone (36 μM), styrene (43 μM), anisole (37 μM), alpha-pinene (5 μM), 1-octen-3-ol (26 μM), benzaldehyde (64 μM), and 2-ethyl-1-hexanol (27 μM). Each Petri dish was placed in a plastic box (300 × 200 × H6.5 mm, 2.6-L) with a lid with 14.5-cm long and 1-cm wide rectangular slit covered by a piece of the material attached on the inner side lid by using an adhesive tape. The plastic boxes were placed consecutively in a climate chamber (Memmert HCP 108; VWR, Sweden) adapted for air sampling by having two sampling ports. For purification of the incoming air a tube containing Anasorb 747 (SKC Inc., Eighty Four, PA, USA) was used in one of the ports; chamber air samplings were conducted with a tubing passing through the other port. Air samplings were performed 1 h after the study conditions (30 and 40 °C; 35, 60, and 85% RH) were attained. After the altogether 18 samplings ($n = 1$ for Solution 1; $n = 2$ for Solution 2; where n is number of experiments) plastic boxes with uncovered lids were placed in the chamber and after 1 h sampled at 23 °C and 55% RH, as positive controls. Air samplings were performed during 30 min by pumping through Tenax TA tubes (Solution 1) at 100 ml/min or Anasorb 747 tubes (Solution 2) at 250 ml/min, the sampling tubes being placed outside the chamber. Results were calculated as a percentages of VOCs emissions reductions (due to the device) comparing to the emissions from uncovered boxes.

The effect of RH on the water vapor resistance was also studied. The different RH were achieved by using saturated solutions of magnesium chloride (33% RH) and potassium chloride (85% RH) (purchased from Sigma Aldrich, Schnelldorf, Germany) as described elsewhere (Svennberg and Wadsö, 2003), at an ambient RH of 45%.

2.5. Impact of accelerated aging

Pieces (20 × 12 cm) of the material were stored in the climate chamber at 75 °C and 60% RH (ambient temperature was 23 °C) considering the 10-degree rule (Hukins et al., 2008) where increasing the temperature by 10 °C will cause approximately a doubling of the rate of chemical reactions. The experiment was carried out for up to a hundred days corresponding to 10 years of aging. Samples treated 10, 50 and 100 days as described simulating 1, 5 and 10 years of aging were taken out from the chamber, wrapped in air tight bags, and kept in the dark at room temperature until analyzed for their capability to reduce VOCs emissions as described previously (Markowicz and Larsson, 2012). Parallel samples were analyzed for water vapor resistance at an RH of 85% (ambient RH 45%) as described (Svennberg and Wadsö, 2003).

2.6. Reduction of formaldehyde and 2-chloroanisole

200 μl of formalin, with a 37% formaldehyde concentration (purchased from Sigma Aldrich), were added to 10 ml of distilled water in a Petri dish and placed in a plastic box (300 × 200 × H6.5 mm, 2.6-L). Air concentrations of formaldehyde were measured over the box being either uncovered or covered by the device (Kuwata et al., 1983). Samplings ($n = 2$) were made by pumping air (200 ml/min, 30 min) through DNPH-impregnated C18 columns which were then sent to IVL (Gothenburg, Sweden) for analysis by using high-performance liquid chromatography (HPLC). A similar procedure (Markowicz and Larsson, 2012) was used for studying the effect of the surface emissions trap in blocking emissions due to 2-chloroanisole (50 μM) by using GC–MS.

3. Results

3.1. Case study building

The results are illustrated in Table 1. Decreased air concentrations of 2-ethyl-1-hexanol, from 6–7 μg/m^3 to 2 μg/m^3, were found two months after the device had been applied; the concentrations of 2-ethyl-1-hexanol in the installed material rose from 0 (unused device) to 280.3 μg/g after 13 months of use. Neither the surface of the material, laminated floor, nor the PVC flooring taken 13 months after application of the surface emissions trap contained any hyphae as judged by phase contrast light microscopy of the tape lifts at 400 times magnification.

Table 1
Air concentrations of 2-ethyl-1-hexanol in room B, and amounts of 2-ethyl-1-hexanol extracted from the surface emissions trap, at different time periods after installation of the device.

Time	Air concentrations [μg/m^3]	Adsorbed amounts [μg/g]
Before applying the device	6	0
1 week after application	7	n.a.[a]
2 months after application	2	17.0
4 months after application	n.a.[a]	68.6
8 months after application	2	150.6
13 months after application	2	280.3

[a] Not analyzed.

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Table 2
Emissions from PVC flooring covered and uncovered by the device measured under a desiccator lid after 3 months (toluene equivalents [μg/m^3]). The numbers in the brackets represent a reduction (%) due to the use of surface emissions trap.

Measurement	n-Butanol	2-Ethyl-1-hexanol	TXIB	TVOCs
Uncovered floor	1620	1201	608	11,108
Floor covered with the device	175 (89)	10 (99)	3 (99)	326 (97)

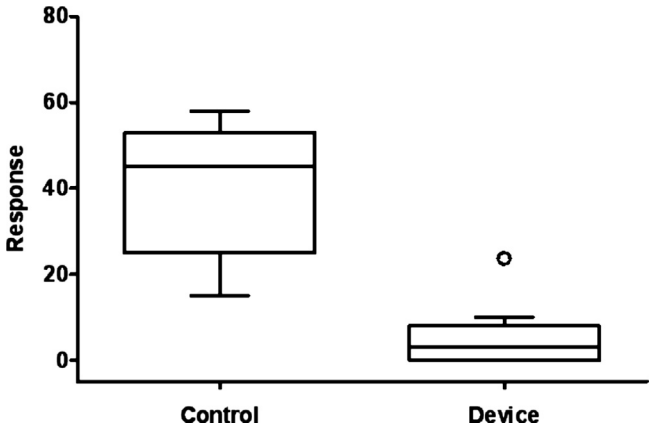

Fig. 1. Human perception of VOCs reduction. Box plot of responses (0–80) among the participants of the "control" and "device" groups.

3.2. Field study of floor emissions

Results are presented in Table 2. Covering the flooring with the device resulted in reduced air concentrations of n-butanol, 2-ethyl-1-hexanol, and TXIB. For example, the TVOCs reduction was 97% whereas 2-ethyl-1-hexanol was reduced by 99%.

3.3. Human perception of VOCs reduction

Out of 24 school teachers only 7 (29%) answered the questionnaire. Four reported that the perceived air quality had improved, two reported no differences (though none of them had experienced any problems with the air), and one reported "I do not know".

In the controlled exposure study the responses for "device" were clustered closely around their median 1 (and had a long tail), while the responses for the "control" were spread over a much wider range and roughly symmetric around their median 45.0 (Fig. 1). The *Mann–Whitney U statistic* was used as implemented in the *coin* package of R (Hothorn et al., 2008). The *p*-value was 0.03108, well below the type-one error 1.0 percent mandated in the design phase (with type-two error of less than 1.0 percent). Associated with the Mann–Whitney statistic is the *Hodges–Lehmann–Sen* estimator of effect, which is the median of the differences in the responses from the "device" and the "control", respectively. This effect was estimated to be 38.0, the effect estimate being a member of the confidence interval [24, 80], which is specified with the conventional 95% confidence.

3.4. Impact of RH, temperature, and accelerated aging

The reductions of the air concentrations of VOCs due to the use of the surface emissions trap are shown in Table 3. The average reduction was 97.8% (Solution 1) and 98% (Solution 2). Lowest reductions in Solution 1 were found for acetone (93.8%) at the highest temperature and RH, and in Solution 2 for 2-ethyl-1-hexanol (87%) at the highest temperature and an RH of 60%. Neither ethanol nor 1-propanol was detected even when the plastic box was uncovered; obviously the concentrations of these (hydrophilic) compounds were below the detection limit. The water vapor resistance was 267 s/m at an RH of 33% and 177 s/m at an RH of 85%.

The average emissions reduction of the aged device was 96.1% for the smaller VOCs (Solution 1) and 99.9% for the larger VOCs (Solution 2), as compared with 99.8% (Solution 1) and 99.5% (Solution 2) for unaged material. The water vapor resistances were 177 (unaged), 194 (1 year), 196 (5 years) and 163 (10 years) s/m, respectively.

3.5. Reduction of formaldehyde and 2-chloroanisole

The air concentration of formaldehyde over the plastic box, 650 μg/m^3, was reduced by 98.5% following application of the material. Correspondingly, the air concentration of 2-chloroanisole was reduced by 99%.

Table 3
Air concentrations of VOCs over uncovered plastic boxes, reductions in VOCs air concentrations over parallel boxes covered with the surface emissions trap at different temperatures and RH. A 100% reduction denotes amounts below the detection limit.

Compound	Air concentration [μg/m^3]	% Reduction (°C/RH)					
		30/35	30/60	30/85	40/35	40/60	40/85
Acetone	72	97.2	96.5	96.0	96.0	95.3	93.8
2-Methylfuran	234	98.7	98.9	99.0	99.7	99.6	99.5
Ethyl acetate	185	97.0	98.7	98.1	98.8	98.2	97.6
Benzene	350	96.7	97.5	97.9	99.6	99.5	99.4
2-Methyl-1-propanol	32	97.5	97.8	97.2	97.8	97.2	96.9
1-Methoxy-2-propanol	3	96.7	96.7	96.7	96.7	100	100
1-Butanol	5250[a]	99.7	99.5	98.7	99.3	98.3	96.8
3-Methyl-2-butanol	5967[a]	99.9	99.7	99.5	99.5	98.8	98.2
3-Methylbutanol	3991[a]	99.9	99.8	99.5	99.6	98.9	99.5
Dimethyl disulfide	7279[a]	99.7	99.4	99.4	99.2	98.8	98.6
Hexanal	5108[a]	99.8	99.7	99.7	99.7	99.6	99.4
2-Heptanone	3129[a]	99.8	99.7	99.6	99.8	99.7	99.6
Styrene	707[a]	98.7	98.1	98.3	98.0	96.5	96.4
Anisole	338[a]	98.9	98.3	98.6	98.1	96.7	95.7
Alpha-pinene	658[a]	99.4	99.2	99.3	99.1	98.9	98.6
1-Octen-3-ol	132[a]	99.0	97.8	98.8	98.1	97.4	96.3
Benzaldehyde	330[a]	99.7	99.7	99.6	98.9	98.3	97.7
2-Ethyl-1-hexanol	64[a]	90.6	90.3	91.2	88.1	87.0	87.6

[a] Toluene equivalents.

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4. Discussion

This study shows that attaching a surface emissions trap cloth to a surface from which moisture-driven emissions are spread can prevent humans from being exposed to such emissions. In the studied room (room B) air concentrations of 2-ethyl-1-hexanol were 6–7 μg/m^3 before the device was installed suggesting emissions from the floor. In the field study the material accounted for a 99% reduction in air concentrations of the same compound. 2-Ethyl-1-hexanol in indoor air is frequently related to chemical (Björk et al., 2003) or microbial (Nalli et al., 2006) degradation of plasticizers in a PVC flooring and/or in the glue used to attach a PVC flooring on concrete in case the concrete has not been enough dry when gluing or when moisture, in the absence of a moisture barrier, has been allowed to diffuse from the ground up to the floor. In a study on hospital buildings Norbäck et al. (2000) showed that floor emissions of 2-ethyl-1-hexanol, in concentrations of 2–32 μg/m^3, may be related to increased symptoms of asthma. In the air of room B, apart from 2-ethyl-1-hexanol, we also found traces of phenol, n-decane and n-hexanal, as well as 5 unidentified aliphatic hydrocarbons (data not shown), indicating that the bad indoor air quality perceived by the pupils and staff may have resulted from a combination of different VOCs. Research has shown that mixtures of VOCs emitted from building materials may act in synergy in worsening the perceived air quality (Knudsen et al., 1999; Patterson et al., 1993) even when present in concentrations below the odor thresholds.

The remediation was made because of the complaints from the pupils and staff. The fact that the air concentration of 2-ethyl-1-hexanol did not decrease immediately after the device had been applied on the floor may be due to absorption of the compound in the ceiling or walls, diffusing from these surfaces back into the air after the floor emissions had been stopped. This so-called sink effect, where building materials act as buffers for VOCs, has been described (Meininghaus et al., 2000; Xiong et al., 2008; Zhang et al., 2002a). It has even been suggested that VOCs may diffuse through walls from one room to another and that different barriers may be used to prevent such diffusion (Meininghaus et al., 2000). The odor problems in the studied school disappeared shortly (a few days) after application of the material and rooms A and B could again be used as before the air quality complaints. Interestingly, this improvement in the perceived air quality was noticed well before the air concentrations of 2-ethyl-1-hexanol had started to decrease indicating that the problems were caused by substances other than 2-ethyl-1-hexanol. Most of the comments among the school staff stated that installing the surface emissions trap had led to an improved air quality; however, for obvious reasons the staff might have been biased being aware of the surface emissions trap installation. The blinded exposure test, with healthy male students, revealed clearly that the cloth efficiently blocked the odor of the studied chemicals mixture.

We found no obvious effect of the different temperatures and RHs on the capability of the device in reducing VOCs. The water vapor resistance was higher at an RH of 33% than at 85%; still, the values were very low. The accelerated aging simulating up to 10 years product lifetime showed no clear effect on the performance of the device or its water vapor resistance. The fact that no hyphae were found neither on the cloth, the laminated floor, nor the PVC flooring 13 months after application of the device in room B showed that the installed flooring, at the prevailing humidity (not measured) did not allow mold growth. The amounts of 2-ethyl-1-hexanol in the cloth pieces taken under the laminate flooring in room B increased from 17.0 (2 months after installation) to 280.3 (13 months after installation) μg/g in a linear manner ($R^2 = 0.9975$) suggesting a constant emission rate of 2-ethyl-1-hexanol from the floor. Notably, we found previously that the adsorption capacity of the device is 27.1 mg/g (Markowicz and Larsson, 2012). In the studied case only around 1% of the adsorption capacity of the device was consumed after 13 months of use. Clearly, since the adsorption capacity of the device is limited it should be used with this restriction in mind.

The device has previously been shown to be able to efficiently reduce a range of VOCs including alcohols, aldehydes, ketones, terpenes, aromatic hydrocarbons, sulfides etc. (Markowicz and Larsson, 2012). In the present study it was shown that the device also can reduce formaldehyde (a common emission product from building materials used indoors) by 98.5% and 2-chloroanisole (from moist impregnated wood) by 99%. The surface emissions trap may represent a convenient, health-effective and environment-friendly way of improving indoor air in cases when the problems are due to emissions from surfaces of the building indoors. Further studies should include an unbiased evaluation of the perceived the air quality in buildings following cloth installation. Further studies are also required for being able to evaluate if the device, due to its ability to reduce emissions, also will be useful for saving energy by allowing a lowered ventilation rate or a reduced need for conventional electricity-driven air cleaners while at the same time maintaining a satisfactory indoor air quality.

5. Conclusions

Emissions of VOCs (including odors) from a surface may be stopped efficiently by applying the cloth on the surface. In the present study, attaching the surface emissions trap on a PVC flooring in a school with air complaints led to a clear improvement in the perceived air quality and decreased 2-ethyl-1-hexanol air concentrations. The device may constitute a useful means of restoring the indoor air quality e.g. after water damage leading to unwanted emissions indoors.

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References

Bernstein, J.A., Alexis, N., Bacchus, H., Bernstein, I.L., Fritz, P., Horner, E., Li, N., Mason, S., Nel, A., Oullette, J., Reijula, K., Reponen, T., Seltzer, J., Smith, A., Tarlo, S.M., 2008. The health effects of nonindustrial indoor air pollution. J. Allergy Clin. Immunol. 121, 585–591.

Björk, F., Eriksson, C.A., Karlsson, S., Khabbaz, F., 2003. Degradation of components in flooring systems in humid and alkaline environments. Constr. Build Mater. 17, 213–221.

Clausen, G., 2004. Ventilation filters and indoor air quality: a review of research from the International Centre for Indoor Environment and Energy. Indoor Air 14 (Suppl. 7), 202–207.

Fisk, W.J., Faulkner, D., Palonen, J., Seppanen, O., 2002. Performance and costs of particle air filtration technologies. Indoor Air 12, 223–234.

Groves, R.M., Fowler, F.J., Couper, M.P., Lepkowski, J.M., Singer, E., Tourangeau, R., 2009. Survey Methodology, second ed. John Wiley & Sons, New Jersey.

Haverinen-Shaughnessy, U., Hyvarinen, A., Putus, T., Nevalainen, A., 2008. Monitoring success of remediation: seven case studies of moisture and mold damaged buildings. Sci. Total Environ. 399, 19–27.

Hothorn, T., Hornik, K., Wiel, M.A.v.d, Zeileis, A., 2008. Implementing a class of permutation tests: the coin package. J. Stat. Softw. 28 (8), 1–23.

Hukins, D.W., Mahomed, A., Kukureka, S.N., 2008. Accelerated aging for testing polymeric biomaterials and medical devices. Med. Eng. Phys. 30, 1270–1274.

Knudsen, H.N., Kjaer, U.D., Nielsen, P.A., Wolkoff, P., 1999. Sensory and chemical characterization of VOC emissions from building products: impact of concentration and air velocity. Atmos. Environ. 33, 1217–1230.

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Kolarik, J., Wargocki, P., 2010. Can a photocatalytic air purifier be used to improve the perceived air quality indoors? Indoor Air 20, 255–262.
Kuwata, K., Uebori, M., Yamasaki, H., Kuge, Y., Kiso, Y., 1983. Determination of aliphatic aldehydes in air by liquid chromatography. Anal. Chem. 55, 2013–2016.
Markowicz, P., Larsson, L., 2012. The surface emissions trap: a new approach in indoor air purification. J. Microbiol. Methods 91, 290–294.
Meininghaus, R., Gunnarsen, L., Knudsen, H.N., 2000. Diffusion and sorption of volatile organic compounds in building materials – impact on indoor air quality. Environ. Sci. Technol. 34, 3101–3108.
Mendell, M.J., Mirer, A.G., Cheung, K., Tong, M., Douwes, J., 2011. Respiratory and allergic health effects of dampness, mold, and dampness-related agents: a review of the epidemiologic evidence. Environ. Health Perspect. 119, 748–756.
Nalli, S., Horn, O.J., Grochowalski, A.R., Cooper, D.G., Nicell, J.A., 2006. Origin of 2-ethylhexanol as a VOC. Environ. Pollut. 140, 181–185.
Nicolas, M., Ramalho, O., Maupetit, F., 2007. Reactions between ozone and building products: Impact on primary and secondary emissions. Atmos. Environ. 41, 3129–3138.
Norbäck, D., Wieslander, G., Nordström, K., Wålinder, R., 2000. Asthma symptoms in relation to measured building dampness in upper concrete floor construction, and 2-ethyl-1-hexanol in indoor air. Int. J. Tuberc. Lung Dis. 4, 1016–1025.
Patterson, M.Q., Stevens, J.C., Cain, W.S., Cometto-Muñiz, J.E., 1993. Detection thresholds for an olfactory mixture and its three constituent compounds. Chem. Senses 18, 723–734.
R Development Core Team, 2012. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria, ISBN 3-900051-07-0. Available online at: http://www.R-project.org/.
Rohr, A.C., Wyzga, R.E., 2012. Attributing health effects to individual particulate matter constituents. Atmos. Environ. 62, 130–152.
Rudblad, S., Andersson, K., Stridh, G., Bodin, L., Juto, J.E., 2002. Slowly decreasing mucosal hyperreactivity years after working in a school with moisture problems. Indoor Air 12, 138–144.
Sahlberg, B., Gunnbjörnsdottir, M., Soon, A., Jogi, R., Gislason, T., Wieslander, G., Janson, C., Norbäck, D., 2013. Airborne molds and bacteria, microbial volatile organic compounds (MVOC), plasticizers and formaldehyde in dwellings in three North European cities in relation to sick building syndrome (SBS). Sci. Total Environ. 444, 433–440.
Sjöberg, A., Ramnäs, O., 2007. An experimental parametric study of VOC from flooring systems exposed to alkaline solutions. Indoor Air 17, 450–457.
Sublett, J.L., Seltzer, J., Burkhead, R., Williams, P.B., Wedner, H.J., Phipatanakul, W., Allergy, A.A., 2010. Air filters and air cleaners: rostrum by the American Academy of Allergy, Asthma & Immunology Indoor Allergen Committee. J. Allergy Clin. Immunol. 125, 32–38.
Sunesson, A.L., Liljelind, I., Sundgren, M., Pettersson-Stromback, A., Levin, J.O., 2002. Passive sampling in combination with thermal desorption and gas chromatography as a tool for self-assessment of chemical exposure. J. Environ. Monitor. 4, 706–710.
Svennberg, K., Wadsö, L., 2003. A modified cup-method for lightweight and highly permeable materials. In: Proceedings of Research in Building Physics, pp. 177–182.
Tuomainen, A., Seuri, M., Sieppi, A., 2004. Indoor air quality and health problems associated with damp floor coverings. Int. Arch. Occup. Environ. Health 77, 222–226.
Uhde, E., Salthammer, T., 2007. Impact of reaction products from building materials and furnishings on indoor air quality – a review of recent advances in indoor chemistry. Atmos. Environ. 41, 3111–3128.
Weschler, C.J., 2004. Chemical reactions among indoor pollutants: what we've learned in the new millennium. Indoor Air 14 (Suppl. 7), 184–194.
Weschler, C.J., 2006. Ozone's impact on public health: contributions from indoor exposures to ozone and products of ozone-initiated chemistry. Environ. Health Perspect. 114, 1489–1496.
Wolkoff, P., Clausen, P.A., Wilkins, C.K., Nielsen, G.D., 2000. Formation of strong airway irritants in terpene/ozone mixtures. Indoor Air 10, 82–91.
Xiong, J.Y., Zhang, Y.P., Wang, X.K., Chang, D.W., 2008. Macro-meso two-scale model for predicting the VOC diffusion coefficients and emission characteristics of porous building materials. Atmos. Environ. 42, 5278–5290.
Zhang, J.S., Zhang, J.S., Chen, Q., Yang, X., 2002a. A critical review on studies of volatile organic compound (VOC) sorption by building materials. ASHRAE Trans. 108 (1), 162–174.
Zhang, Q., Feddes, J.J.R., Edeogu, I.K., Zhou, X.J., 2002b. Correlation between odour intensity assessed by human assessors and odour concentration measured with olfactometers. Can. Biosyst. Eng. 44 (6), 27–32.
Zhang, Y.P., Mo, J.H., Li, Y.G., Sundell, J., Wargocki, P., Zhang, J.S., Little, J.C., Corsi, R., Deng, Q.H., Leung, M.H.K., Fang, L., Chen, W.H., Li, J.G., Sun, Y.X., 2011. Can commonly-used fan-driven air cleaning technologies improve indoor air quality? A literature review. Atmos. Environ. 45, 4329–4343.

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