Trade-offs between ventilation rates and formaldehyde concentrations in new-build dwellings in the UK

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ABSTRACT

The current policies and regulatory frameworks in the construction sector aim to improve energy efficiency of new buildings whilst maintaining acceptable level of indoor environmental quality (IEQ) including indoor air quality (IAQ). In practice, however, there are often important trade-offs between these objectives. The aim of this paper is to investigate the concentrations of volatile organic compounds (VOCs) in a recently built residential block in the UK and the potential trade-offs between ventilation rates and VOCs. Concentration levels of VOCs that are likely to have concentrations higher than their respective exposure limit values (ELVs) in low energy dwellings were measured in five sample apartments in this block during typical weeks in winter and summer using diffusive sampling methods. Whilst most target VOCs had concentrations lower than ELVs, benzene and formaldehyde levels were regularly higher than the limits. Measurement of outdoor concentrations showed that benzene levels were predominantly driven by outdoor sources whilst formaldehyde concentrations were driven by internal sources including construction material and furniture. To investigate how formaldehyde levels can be reduced in a given context determined by typical material used in the industry, two models were developed to calculate the effect of enhanced ventilation on formaldehyde levels and energy efficiency of the apartment with highest formaldehyde. Lack of clear definition of VOC characteristics of building material and ever-increasing use of material with high formaldehyde emission factors such as medium-density fibreboard (MDF) in indoor furniture may contribute to high formaldehyde concentrations in indoor air. The study found that to offset the effect of the existing internal sources in the case study apartment and comply with the best practice ELV for formaldehyde, the ventilation rate should be more than three times the existing rate required in the current Building Regulations, and this can significantly increase energy use. Formaldehyde is currently not regulated in the UK Building Regulations. Given the potential health impact of high formaldehyde concentrations and the empirical evidence, it is necessary to cover formaldehyde in the next edition of the Building Regulations. This study points to the significance of improving the existing regulations and standards to clearly define maximum permissible emission factors for various VOCs in building material and indoor furniture. It is also important to improve source control measures to reduce the concentration of formaldehyde. These measures may be complemented by enhanced ventilation. It is, however, necessary to investigate the implications of enhanced ventilation for energy efficiency.

KEYWORDS

Indoor Air Quality (IAQ), Energy Efficiency, Volatile Organic Compounds (VOCs), Formaldehyde, Dwellings

1 INTRODUCTION

As building fabric, air tightness, and building services standards become ever more stringent to help the quest for energy efficiency, there is a risk that the ventilation rates may be compromised to save more energy as other energy efficiency measures reach their technical and economic limit. Meanwhile our understanding of indoor air quality (IAQ) and its key determinants is evolving. Whilst most building codes and regulations are primarily focused on human-induced carbon dioxide levels as a proxy for ventilation rates and IAQ, there are major other internal sources for pollution that should also be considered including volatile organic compounds (VOCs) driven by construction material and furniture. Exposure limit values

(ELVs) set out for VOCs consider the latest epidemiological evidence of their likely effect on humans and are updated accordingly. This may have implications for the control of internal sources of pollution (emission factors of construction material and furniture), ventilation rates required, and energy efficiency.

This paper aims to investigate the concentration level of several VOCs, which are likely to have high concentration levels based on previous studies, in a recently built residential block in East London, and identify how IAQ can be improved in dwellings. As the exchange of air between outdoor and indoor in dwellings is typically lower than non-domestic buildings, concentrations of VOCs driven by internal sources could be problematic and should be considered as a key determinant of IAQ. Key objectives of the study are as follows:

- To measure concentrations of VOCs in typical residential units that represent current construction material and furniture commonly used,
- Identify critical VOC(s) in the given context,
- Investigate the trade-off between ventilation rates and VOC levels,
- Draw conclusions for improvement of IAQ in new dwellings.

2 BACKGROUND

The IEA-EBC Annex 68 project aims to address indoor air quality design and control in low energy residential buildings. An extensive meta-data analysis on several studies of residential buildings was carried out in Subtask 1 of this project to define metrics for IAQ. This led to identification of pollutants that are likely to have concentration levels higher than respective ELVs in low-energy dwellings (Figure 1). In addition to particulate matter and nitrogen dioxide, several VOCs were identified as high-risk pollutants in low energy dwellings. While fine particulate matter (PM2.5) and nitrogen dioxide (NO_2) are predominantly driven by outdoor sources and filtration of outdoor air (e.g. particle filters and activated carbon filter for NO_2) can help reduce their concentration in indoor air, most VOCs are driven by internal sources. Therefore, there is a potential conflict between energy efficiency measures focusing on ventilation demand and IAQ when VOCs are considered as proxy for IAQ. It is also notable that individual VOCs such as VOCs reported in Figure 1are not currently regulated in the UK Building Regulations. It is therefore important to investigate the IAQ performance of low energy dwellings procured in accordance with this regulatory framework with respect to the VOCs identified in IEA-EBC Annex 68 and identify improvement opportunities.

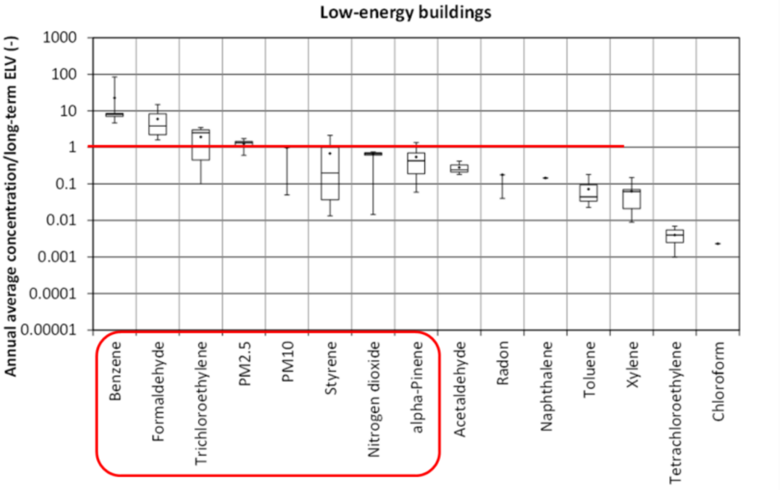


Figure 1. High risk contaminants in low-energy dwellings, adapted from Salis et al., 2017

The Building Regulations in the UK are devolved to the four countries of the United Kingdom. Although there are slight differences between the regulations in England, Northern Ireland, Scotland and Wales, the same fundamental principles apply to all. In England, Approved Document Part L1A, a second-tier document in support of Part L of the Building Regulations, sets out detailed requirements for energy performance of new dwellings (HM Government, 2016).

According to Criterion 1 of Approved Document Part L1A, the carbon dioxide emissions associated with regulated energy use of a new dwelling should not be greater than a Target Emission Rate (TER) set out for that dwelling. TER for a new dwelling is determined by applying prescribed fabric characteristics to the geometry of the dwelling and prescribed building services efficiencies. Designers therefore have some flexibility for trade-offs between various energy efficiency measures in the actual building as long as total calculated carbon dioxide emissions are not greater than the TER.

Other requirements in Part L1A address: Target Fabric Energy Efficiency (TFEE), limits on design flexibility (maximum permissible U values and minimum efficiencies required for building services), limiting the effects of heat gains in summer (to mitigate the risk of overheating whilst improving energy efficiency), consistency between design and construction, and provision of information for energy-efficient operation of dwellings.

Indoor air quality, on the other hand, is covered by Approved Document Part F (HM Government, 2013). This Approved Document sets out the ventilation requirements for buildings. It is therefore predominantly focused on means of ventilation rather than setting out exposure limit values for various airborne pollutants. Performance criteria for nitrogen dioxide, carbon monoxide, and TVOC have been defined for dwellings. No performance criteria, however, has currently been defined for specific VOCs.

3 METHOD

The diffusive sampling method, in accordance with ISO 16017 series, was used to measure the average concentrations of volatile organic compounds (VOCs) with risk of concentrations higher than long-term/chronic exposure limit values (ELVs) in new low energy dwellings (Salis, et al., 2017). Concentration levels of benzene, formaldehyde, trichloroethylene, styrene, naphthalene, toluene, and tetrachloroethylene were measured in living room, kitchen and one bedroom of five sample apartments in a recently built residential block during typical weeks in heating season and summer of 2018. Passive tubes and absorbent pads were also installed outdoors to identify the indoor/outdoor trends and sources.

To give context to IAQ monitoring results, a perfluorocarbon tracer (PFT) gas method (Persily, 2016) was used to infer the average air exchange rates in the monitored zones of the sample apartments.

Finally, the trade-off between the VOC with high concentration levels, airflows, and energy efficiency was investigated using IA-QUEST tool for the analysis of IAQ and Standard Assessment Procedure (SAP 2012) tool used for analysis of energy performance of dwellings in England.

IA-QUEST tool is underpinned by the material emission database originally compiled in MEDB-IAQ project instigated by the National Research Council Canada (Won, et al., 2005). The database includes the emission factors derived from testing materials in a flow-through chamber in accordance with ASTM Standard D5116-97 (ASTM International, 1997). This database was used to estimate the emission factors of various materials in the case study, as there is very limited information about emission factors of specific VOCs for construction material used in the UK. This is a consequence of the current regulatory framework and building sustainability codes such as BREEAM that are predominantly based on TVOC rather than individual VOCs.

4 OVERVIEW OF THE CASE STUDY

To investigate Indoor Air Quality (IAQ) in low energy residential buildings, two recently built apartment blocks constructed as part of a regeneration scheme in East London were selected as a case study.

Apartment blocks A and B were completed in December 2014 and January 2015 respectively. Block A is a 13-storey building; Block B has 9 floors. These buildings are located next to each other and close to two main roads in the London Borough of Tower Hamlets in East London. There are 98 flats and maisonettes (two-storey apartments) in these blocks. The buildings were designed with target air permeability of 2-3 $m^3/hr./m^2$ at 50 Pa pressure difference which is significantly lower than 10 $m^3/hr./m^2$ limit set out in the Building Regulations (HM Government, 2013). Consequently, mechanical ventilation with heat recovery (MVHR) was specified to ensure adequate background ventilation is provided to these apartments. Heating is provided by a community heating scheme that is currently gas-fired with provisions for integration of a combined heat and power (CHP) plant in future. There is no mechanical cooling. Figure 2 shows a picture of this development. Table 1 provides background information about the sample apartments included in IAQ investigations. The air permeability reported for each dwelling is based on pressure test result carried out after building completion.

Figure 2. Image of the two apartment blocks covered in the study (left)

Table 1. Background information about sample apartments

Dwelling	Type	Gross Floor Area (m^2)	Floor level	Orientation	Bedroom no.	Occupant no. (steady mode)	Air tightness ($m^3/hr/m^2$ @ 50 Pa)
Apt. 1	Flat	100	Block A, 7th floor	South/West	3	3	3.3
Apt. 2	Flat	100	Block A, 8th floor	South/West	3	5	2.2
Apt. 3	Flat	100	Block A, 9th floor	North/West	3	5	2.0
Apt. 4	Maisonette	127	Block B, Ground floor	South/East	5	7	3.8
Apt. 5	Maisonette	106	Block B, 8th floor	East	3	4	2.9

According to Approved Document Part F the whole dwelling ventilation rate for the supply of air to the habitable rooms in a dwelling should be no less than what is prescribed in Table 2. This was the basis for the commissioning of the MVHR systems in the sample dwellings.

Table 2. Whole dwelling ventilation rates (HM Government, 2013)

	Number of bedrooms in dwelling				
	1	**2**	**3**	**4**	**5**
Whole dwelling ventilation rate (L/s)	13	17	21	25	29
Notes: - In addition, the minimum ventilation rate should be not less than 0.3 L/s per m² of internal floor area. (This includes all floors, e.g. for a two-storey building add the ground and first floor areas.) - This is based on two occupants in the main bedroom and a single occupant in all other bedrooms. This should be used as the default value. If a greater level of occupancy is expected, add 4 L/s per occupant.					

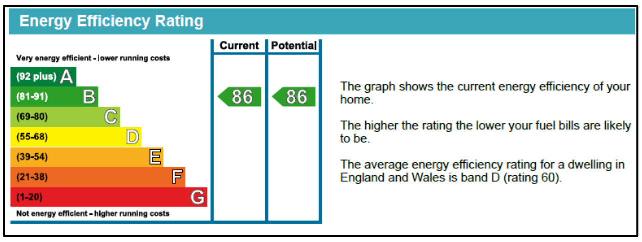
Table 3 reports the U values of the building fabric.

Table 3. U values for the building fabric against the regulatory limits

Building fabric	**Case study (W/m².K)**	**Regulatory limit (W/m².K)**
External walls	0.18-0.19	0.30
Windows	0.85-0.92	2.00
Doors	1.30	2.00
Roof	0.18	0.20
Exposed floor	0.12	0.25

Figure 3 shows a sample Energy Performance Certificate (EPC) that represents Apt. 1. Other dwellings also have the same energy-rating band. Calculated primary energy use per square meter of floor area in the sample apartments Apt. 1 – Apt. 5 is within 56-81 kWh/m² per year.

Figure 3. Energy efficiency rating of the case study dwellings



The graph shows the current energy efficiency of your home.

The higher the rating the lower your fuel bills are likely to be.

The average energy efficiency rating for a dwelling in England and Wales is band D (rating 60).

5 RESULTS

5.1 EMPIRICAL INVESTIGATIONS

Table 4 includes the key statistics for the VOC measurements carried out in the study. Formaldehyde and benzene were the contaminants with concentrations consistently higher than the respective ELVs. Measurements of outdoor formaldehyde levels confirmed that, contrary to benzene, formaldehyde concentrations are driven by material emissions and internal sources, this contaminant was therefore selected for a more detailed investigation.

Table 4. Key statistics for the VOC measurements of five sample apartments

VOC	**Min**	**25th pctl.**	**Median**	**Average**	**75th pctl.**	**Max**	**Annex 68 ELV**
Benzene	**0.55**	**0.55**	**1.20**	**1.14**	**1.48**	**2.8**	**0.2**
Formaldehyde	1.15	**10.15**	**16.32**	**16.78**	**26.13**	**31.91**	**9**
Trichloroethylene	0.25	0.25	0.25	0.26	0.25	0.3	2
Styrene	0.30	0.63	1.35	1.78	2.00	**53.9**	30
Naphthalene	0.25	0.34	1.00	1.38	1.30	**5.4**	2
Toluene	0.45	1.20	2.15	4.03	3.33	22.8	250
Tetrachloroethylene	0.30	0.35	0.35	0.66	1.09	1.8	100

Table 5 lists the formaldehyde levels recorded in sample apartments and the total air change rates derived from PFT measurement during the sampling period. The figures highlighted in bold represent concentration levels higher than the most stringent chronic ELV for formaldehyde set out by the US Environmental Protection Agency (i.e. 9 μg/m^3).

It is notable that formaldehyde levels were generally higher in winter although emission factors are expected to increase with temperature in summer. This can be explained by higher air change rates measured in summer when in addition to background ventilation provided by the MVHR system building occupants also open windows and balcony doors more frequently and for a more prolonged period compared to winter.

Table 5. Formaldehyde levels and air change rates in the sample apartments

Apartment		**Formaldehyde concentration (μg/m^3)**			**ACH (PFT measurement)**
		Living room	**Kitchen**	**Bedroom**	
Apt. 1	Winter	**22.62**	**18.75**	**15.29**	n/a
	Summer	**9.75**	6.15	**23.91**	1.51 ± 0.15 h^{-1}
Apt. 2	Winter	**18.82**	**17.35**	5.04	0.36 ± 0.05 h^{-1}
	Summer	6.60	5.86	5.70	2.24 ± 0.34 h^{-1}
Apt. 3	Winter	**29.25**	**26.87**	**29.53**	0.56 ± 0.08 h^{-1}
	Summer	**11.57**	**11.36**	**31.91**	0.42 ± 0.34 h^{-1}
Apt. 4	Winter	**21.23**	**31.35**	**27.44**	0.86 ± 0.16 h^{-1}
	Summer	**12.82**	**13.74**	**11.84**	0.92 ± 0.14 h^{-1}
Apt. 5	Winter	**28.26**	**22.33**	**27.59**	1.15 ± 0.21 h^{-1}
	Summer	6.41	5.96	**12.44**	2.68 ± 2.97 h^{-1}

Figure 4 shows the correlation between formaldehyde levels and PFT measurements in respective zones (living room, kitchen and bedroom). There is a large degree of scatter in data as multiple other factors affect concentration levels and could not be controlled in this study that was conducted post-occupancy. These factors include changes in environmental parameters such as temperature and relative humidity, occupant behaviour, new furniture and equipment, etc. Nonetheless, there is a clear link between air change rates and formaldehyde levels and the concentrations significantly come down at high air change rates. The median formaldehyde concentration level in low energy dwellings reviewed in Subtask 1 of IEA EBC Annex 68 was 25.9 μg/m^3 (Salis, et al., 2017). The ELV defined for formaldehyde in Well Building Standard is 27 ppb (34 μg/m^3) (International Well Building Institute, 2014). The recorded formaldehyde levels for the case study are therefore generally lower than the past empirical data and other ELVs defined for formaldehyde.

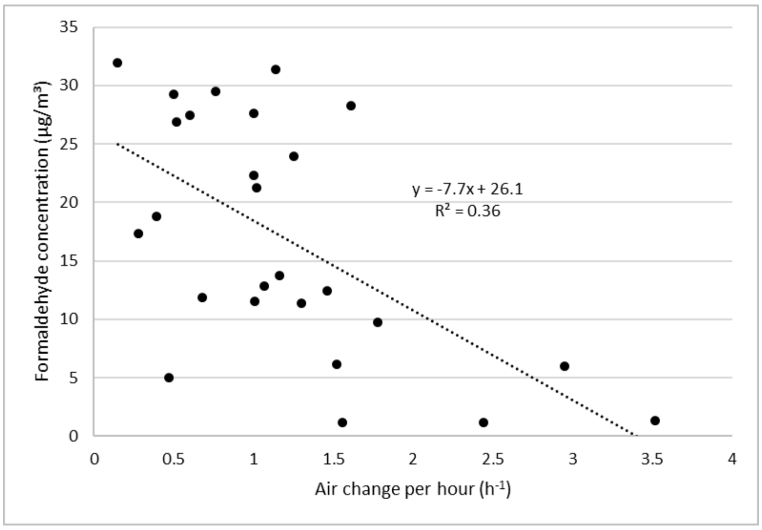


Figure 4. Formaldehyde concentrations against air change rates in sample apartments

Figure 5 shows the range of operative temperatures and relative humidity recorded in the sample dwellings to put formaldehyde concentrations reported in Table 5 in context (measurement accuracy: T: ± 0.4 °C, RH: ± 4.5 %).

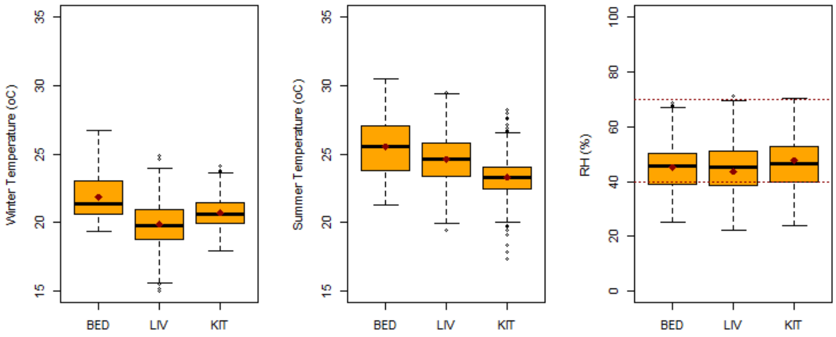


Figure 5. Range of operative temperatures and relative humidity in sample dwellings

The ELV for formaldehyde originally defined by CalEPA, and endorsed by US EPA, is much lower than other limits proposed for this contaminant. The process used by CalEPA to define reference exposure levels for contaminants includes the following steps (CalEPA, 2008):

- conduct literature search
- choose best study, emphasizing human data
- identify critical biological endpoint
- estimate threshold for effect
- temporal/dosimetric adjustments
  (time extrapolation, Human Equivalent Concentrations, children's HEC, physiologically-based pharmacokinetic models)
- Account for uncertainties in data

The special attention to temporal/dosimetric adjustments in CalEPA method may be a key driver for the stringent limit defined for formaldehyde. This ELV can therefore represent the best practice figure and it would be helpful to investigate how this could be achieved given the current construction methods and material used in the industry.

5.2 BUILDING PERFORMANCE SIMULATIONS

A single-zone model was developed for APT. 4, the apartment with high formaldehyde concentrations in both seasons, in IA-QUEST. The emissions database available in IA-QUEST was used to estimate the emission factors for interior material used in the apartment. The information about the apartment including geometry and material specification was collated through the architectural drawings, technical specifications and site visit. The emission factors and power law equations derived from curve fitting in IA-QUEST are based on emission tests lasting from 72-362 hours for dry materials and 78-440 hours for wet materials (Won, et al., 2005). It is assumed that the concentration decay rate derived from these tests are representative of long-term performance and therefore the entire post-occupancy period was taken into account in the simulation. Table 6 includes the list of construction material categories, respective areas and emissions factors used in IA-QUEST.

The air change rate used for the base model was 0.5 h^{-1} that is consistent with specification of the MVHR system and typical for new dwellings in England following Part F requirements. Figure 6 shows that formaldehyde levels at the end of simulation are very close to the measured values reported in Table 5 for Winter.

Table 6. Material and emission factors used for simulation of formaldehyde levels in Apt. 4

Construction material category	**Area (m^2)**	**Nominal emission factor ($\mu g/m^2h$)**	**Maximum emission factor ($\mu g/m^2h$)**
Floor: carpet	63.5	n/a	n/a
Floor: laminate/foam underlay assembly	43.2	37.66	37.70
Floor: kitchen tiles	20.3	n/a	n/a
Paint (ceiling, external wall, partition)	288	n/a	n/a
Door (plywood)	24	n/a	n/a
Kitchen & other cabinets, top only (Melamine/PB)	30	3.68	4.57
Medium Density Fibreboard (MDF)	8	441.59	691.81

The base model developed in IA-QUEST was then used to determine how many air changes are required to achieve formaldehyde concentration levels close to the ELV set out by EPA (i.e. best practice ELV). Figure 7 shows that, given the current material and emission sources, formaldehyde concentration levels will be around 9 $\mu g/m^3$ three years after building completion, if minimum 1.6 air change per hour is continuously supplied to the dwelling. This is also consistent with empirical data that generally show low formaldehyde levels at air change rates greater than 1.6 h^{-1} (Figure 4). It should however be noted that emission factors used in IA-QUEST are based on standard environmental conditions used during emission testing (23 °C, 50% RH). The low formaldehyde levels in Figure 4, on the other hand, generally represent high air change rates achieved in summer when operable windows and doors supplement the operation of MVHR system and temperatures can be higher than test conditions.

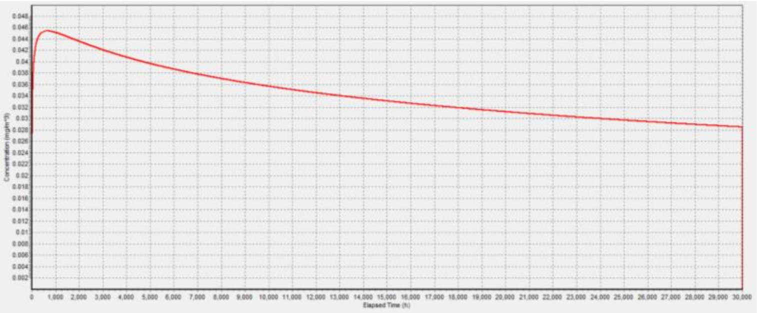


Figure 6. Simulation of formaldehyde levels in Apt. 4 (ACH= 0.5)

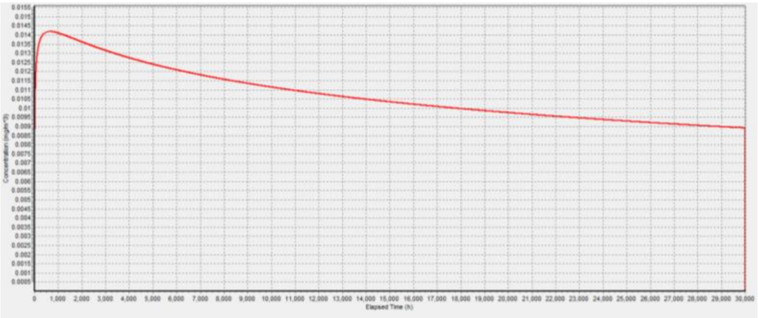


Figure 7. Simulation of formaldehyde levels in Apt.4 (ACH = 1.6)

The implication of this increase in air change rate for energy performance was investigated with an energy performance model developed using SAP tool for Apt. 4.

Increasing the air change rate from 0.5 to 1.6 h^{-1} with the same MVHR system settings in Apt. 4 will increase the primary energy use of regulated energy end-uses by around 22%[1]. If the small power load is also accounted, the increase in primary energy use will be around 11%. It is possible to offset part of this excess in energy use by making improvements in the MVHR system and heating efficiency. In the sample dwelling, the following improvements in energy efficiency measures were considered technically and economically feasible:

- increasing thermal efficiency of the MVHR system from 85% to 90%,
- reducing the specific fan power of the MVHR system from 1.0 to 0.6 W/L/s,
- improving seasonal heating efficiency from 87% to 90%.

These improvements can reduce the excess in primary energy use for regulated energy and total energy to 9% and 5% respectively. Further improvements in energy efficiency such as improving building fabric performance and using low or zero carbon technologies will be required to offset the effect of enhanced ventilation completely.

6 DISCUSSION

These results point to the challenge of improving IAQ whilst maintaining the same level of energy performance required by building regulations. Given the ever-increasing requirements for improving energy efficiency, it is very difficult to reduce formaldehyde levels to the best practice value recommended by the EPA without compromising energy performance, unless advanced source control measures are adopted and emission factors are reduced. There is no evidence that emission factors of construction material for specific VOCs including formaldehyde were considered at design stage for the case study. Currently, most suppliers of

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[1] Regulated energy use includes heating, domestic hot water, fans and pumps, and lighting.

material and building designers in the UK at best consider TVOC which is not necessarily a good metric to identify the risks associated with health.

BRE Digest 464 provides good practice recommendations to control VOC emissions from construction products (Yu & Crump, 2002). Low formaldehyde material such as wood-based boards classified as E1 in accordance with BS EN 13986:2004 (BSI, 2005) can be used in construction. California Air Resources Board's Phase 2 standard (CARB2) also sets out requirements for emissions from composite wood products including hardwood plywood, particleboard and MDF. Using CARB2 compliant material can help reduce the emission sources for formaldehyde in low energy dwellings. The United States Environmental Protection Agency Formaldehyde Standards for Composite Wood Products Act (TSCA Title VI) has also established stringent emissions requirements for composite wood products that can help reduce emission sources significantly (EPA, 2018).

It is important to reduce emission sources first and use enhanced ventilation only as a complementary measure if necessary to ensure concentration levels do not exceed the exposure limits. It is also necessary to review the epidemiologic evidence that underpins the ELV recommended by the EPA as the significant discrepancy between this ELV and other exposure limits prescribed for formaldehyde could have serious implications for design and control of ventilation systems in low energy dwellings.

The emission databases available for IAQ modelling do not necessarily represent the emission factor of the construction products currently used in the industry. It is therefore important to develop national databases that represent various building products used and updated emission factors for formaldehyde and other critical VOCs. In addition to MEDB-IAQ database, PANDORA is another emission database that provides emission rates for both gaseous and particulate pollutants. In addition to construction products, PANDORA also covers the effects of occupant behaviour and activities on emission rates (Abadie & Blondeau, 2011). There is currently no national database for VOC emission rates in the UK, but there are calls for definition of exposure limit values for critical VOCs in the next edition of Approved Document Part F that could lead to development of a national register for emission rates in the future.

7 CONCLUSIONS

The results show concentration levels of most VOCs were lower than respective exposure limit values in the case study residential block. Concentration levels of benzene and formaldehyde were, however, higher than the best practice ELVs identified in Subtask 1 of IEA-EBC Annex 68.

As formaldehyde concentration is predominantly driven by internal sources, enhanced ventilation can help reduce its concentrations in indoor air. The study found that given the existing material sources in the case study apartments, which are typical of new low energy dwellings in the UK, the rate of air exchange between indoor and outdoor air should be more than three times the current levels to meet the best practice ELV for formaldehyde.

This significant increase in air change rates has consequences for energy efficiency that may not be entirely offset by cost-effective energy efficiency measures. It is therefore necessary to use best practice methods for source control and use enhanced ventilation only as a complementary measure. Using CARB2 compliant material and following the EPA's new Formaldehyde Standards for Composite Wood Products Act (TSCA Title VI) can help reduce emission sources.

This study shows the significance of the following measures to improve IAQ in new dwellings in the UK:

- Provision of further information about VOC emission factors of the construction products used in the industry,
- Review of the latest epidemiological evidence about the potential chronic effects of VOCs that are prevalent in construction products and built environment,
- National regulations for critical VOCs,
- Labelling and rating schemes for IAQ that go beyond metrics such as CO_2 concentrations and TVOC and address specific health related pollutants,
- Promotion of best practice for construction material, exposure limit values, and ventilation rates in the industry to strike the right balance between IAQ and energy efficiency.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

Abadie, M., & Blondeau, P. (2011). PANDORA database: A compilation of indoor air pollutant emissions. *HVAC&R Research, 17*(4), 602-613.

ASTM International. (1997). ASTM D5116-97, Standard Guide for Small-Scale Environmental Chamber Determinations of Organic Emissions from Indoor Materials/Products (Withdrawn 2006). West Conshohocken, PA: ASTM International.

BSI. (2005). *BS EN 13986:2004, Wood-based panels for use in construction. Characteristics, evaluation of conformity and marking.* London: British Standard Institute.

CalEPA. (2008). *Air Toxics Hot Spots, Risk Assessment Guidelines, Technical Support Document for the Derivation of Noncancer Reference Exposure Levels.* Oakland, CA: California Environmental Protection Agency.

EPA. (2018). *Rule to Implement the Formaldehyde Standards for Composite Wood Products Act.* Washington D.C.: United States Environmental Protection Agency.

HM Government. (2013). *Approved Document F, Ventilation (2010 edition incorporating 2010 and 2013 amendments).* London: NBS.

HM Government. (2013). *Approved Document Part L1A: Conservation of fuel and power in new dwellings (2013 edition).* London: NBS.

HM Government. (2016). *Approved Document Part L1A: Conservation of fuel and power in new dwellings (2013 edition with 2016 amendments).* London: NBS.

International Well Building Institute. (2014). *The Well Building Standard.* New York, NY: International Well Building Institute.

Persily, A. (2016). Field measurement of ventilation rates. *Indoor Air, 26*(1), 97-111.

Salis, L. C., Abadie, M., Wargocki, P., & Rode, C. (2017). Towards the definition of indicators for assessment of indoor air quality and energy performance in low-energy residential buildings. *Energy and Buildings, 152*, 492-502.

Won, D. Y., Magee, R. J., Yang, W., Lusztyk, E., Nong, G., & Shaw, C. Y. (2005). A material emission database for 90 target VOCs. Beijing: The 10th International Conference on Indoor Air Quality and Climate.

Yu, C., & Crump, D. (2002). *BRE Digest 464, VOC emissions from building products.* Watford: BREPress.