

TDTS 55

Using the FLEC to determine emissions of volatile organic compounds from materials and products

Summary

This Application Note describes the principles behind use of the Field & Laboratory Emission Cell (FLEC[®]) for material emissions testing according to standard methods.

Introduction

Characterisation of emissions of volatile and semi-volatile organic chemicals (VOCs and SVOCs) from materials can be carried out using direct thermal desorption¹. Equilibrium headspace techniques are also occasionally used for volatile emissions. However, the most important methodology for material emissions testing requires test chambers or cells, with vapour sampling onto sorbent tubes and TD-GC/MS or FID analysis. Data from such tests allow manufacturers and users to compare products and to evaluate their potential impact on the indoor environment.

Relevant standard methods for material emissions testing include ENV 13419-2 (and -3), ISO 16000-10 (and -11) and ASTM draft standard Work Item WK3368. Associated standard methods for analytical aspects include ASTM D6196-03, ISO 16017-1 and ISO 16000-6.

Background

The FLEC

The FLEC is a small portable device for the determination of VOCs emitted from indoor materials/products (Figure 1), developed in 1990–1991 by a team of Scandinavian scientists^{2,3}. It differs from small chambers in that it has one open wall or 'face' which is placed onto the planar surface of the material under test, so that the material's surface effectively becomes part of the emission cell. Emission cells like FLEC complement large- and small-scale emission chambers – their advantages and disadvantages are discussed in Application Note TDTS 72.

The FLEC can be used for both laboratory measurements and non-destructive emissions testing in the field, and in the Application Note we address the laboratory applications.

The FLEC is constructed of polished, acid-resistant stainless steel. Air enters from a baffle around the perimeter (see inset in Figure 1) and is directed over the entire surface of the test material. The air flow accelerates as it moves towards the exhaust point,

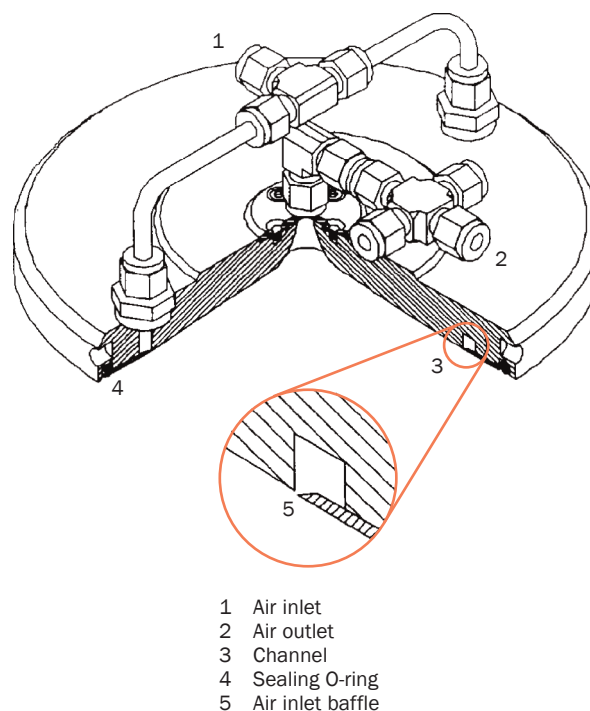


Figure 1: Cutaway diagram of the FLEC.

eliminating sink effects. The temperature, humidity, purity and flow rate of the incoming air are closely controlled.

The FLEC can only be used for materials/products with a (roughly) planar surface. Typical applications include flooring materials (wood-block, carpeting, vinyl flooring, etc.), wood-based panels, sealants, textiles, adhesives, paints, coatings, plastic beads, concrete levelling compounds, wallpaper, plastic sheeting and structural foams. If the test materials are heterogeneous – for example, natural wood containing knots, multiple tests must be carried out on the same sample. Similar restrictions apply to small chambers.

The FLEC can be placed directly onto rigid surfaces, and is held in place by the weight of the cell compressing the sealing gasket or O-ring. Compressible products (e.g. carpets) are placed into a sample holder so that the weight of the cell rests on the rim of the sample holder and does not compress the product itself. A planar sample surface can thus be presented to the cell at the right height, without having any impact on the cell volume or other parameters.

The exhaust air from the FLEC is fully mixed to ensure that air sampled at the exit point is representative of the air in the cell. Approximately 80% of the flow of air into the cell is pumped onto two sample tubes. The excess air is allowed to exit through an overflow vent, so that a slight positive pressure is maintained inside the cell, preventing ingress of background air.

The surface air velocity under the FLEC varies^{4,5} from point-to-point by a factor of about three (this is similar to small chambers⁶), but has a constant distribution. The inlet air flow rate is typically set between 200 and 1400 mL/min, so that the range of surface air velocities has no effect on the area specific emission rate at any point⁷. The effect of surface air velocity is discussed in more detail later.

Emissions tests are carried out at fixed times after preparation of the test specimen – for example after 2 hours, 24 hours, 72 hours, 10 days, 28 days, 56 days or 182 days (26 weeks). Throughout the entire test period, test pieces should be kept under the FLEC, under the flow of pure, humidified air. Alternatively, to increase sample throughput, samples can be stored in a clean, well-ventilated environment, under controlled conditions of temperature and humidity, with no risk of contamination from other samples or other emission sources. However, note that some standard methods require samples to be put back under the FLEC at least 24 hours prior to the next test.

The sample tubes used for collecting VOCs are analysed by TD-GC, usually with MS and FID to identify and quantify the target volatile organic compounds, as described in ASTM D-6196, ISO DIS 16000-6 or ISO 16017-1. The measured masses of volatile organic compounds retained by the sorbent tubes are then used to determine the area specific emission rates of the material or product. Different sampling and analytical techniques are used for formaldehyde (and for other carbonyls) – for example, see ASTM D-5197.

Deriving area-specific emission rates

Below is a summary of the main issues involved in calculating meaningful area-specific emission rates from data acquired using FLEC.

General principles

Area-specific emission rates at a given elapsed time (t) are calculated from the masses of target VOCs collected on the sample tubes, the flow of air pumped through each sample tube, the total flow of air entering the FLEC cell, the duration of the test and the exposed surface area of the test specimen. Area-specific emission rates at a given elapsed time can also be expressed as a function of the emission cell air concentrations for each VOC and the area-specific air flow rate (q).

Using emission data to estimate the contribution to atmospheric VOC concentrations indoors

Provided the area-specific air flow rate over the surface of the test specimen is similar to that found in the built environment, and provided the surface of the material is sufficiently homogeneous to ensure that the area of the test specimen exposed in the emission cell is representative of the whole, area-specific emission rates determined by these tests can be used to estimate the likely contribution to atmospheric VOC concentrations from the material in real-life use, at time t after installation/application (assuming similar nominal conditions of temperature and humidity).

Comparing emission data from FLECs and chambers⁸

Provided test conditions are duplicated, area-specific emission rates generated using FLEC can always be compared with area-specific emission rates produced for the same or similar products by other laboratories using FLEC.

The effect of the emission mechanism on test data

Provided the dominant emission mechanism is (internal) diffusion, not evaporation (external diffusion), area-specific emission rates will be broadly independent of air velocity over the surface of the indoor material. This will remain true provided the surface air velocity exceeds the minimum velocity required to prevent build-up of vapour-phase contaminants at the surface of the material.

Provided the dominant emission mechanism from a material is internal diffusion, it is therefore possible to compare area-specific emission rates generated using the FLEC under different air flow conditions or to compare area-specific emission rate data generated by emission cells with that obtained using test chambers.

However, this is not true of evaporative emissions, which predominate during the drying/curing stages of wet-applied products. These are significantly affected by the following factors:

- Sample storage and preparation conditions
- Timing of the test
- Loading factor (and related vapour concentration within the cell)
- Air velocity over the test specimen surface.

Comparative tests on wet-applied products during the drying/curing stage should therefore be carried out using identical equipment, conditions and procedures, and using an air velocity which approximates to that seen in real-world use⁹⁻¹¹. These restrictions apply in principle to both cells and small chambers.

Note, however, that emissions testing of wet-applied products is typically carried out after the drying/curing stage, when internal diffusion-controlled emission processes predominate. This is more representative of real-world use, as people or animals are unlikely to occupy a room or building until wet-applied coatings have dried or cured.

Precautions for heterogeneous materials

If the indoor material under test is not homogeneous (for example natural wood), the test should be repeated for multiple test specimens in order to establish a mean area-specific emission rate. This is also true in principle for emissions testing using small (<100 L) chambers.

Controlling key test parameters

In order to produce meaningful area-specific emission rates from emission cells or chambers (large or small), the following key parameters must meet minimum performance criteria:

- Background interferences
- Control of humidity and temperature
- Control of the air velocity at the surface of the test specimen
- Thorough mixing of the air, so that the concentration at the sampling (exit/exhaust) point is representative of the air within the emission cell
- Leak tightness
- Recovery and sink effects.

Equipment/apparatus required – Preparing for analysis

A complete emission cell system, designed and operated to determine area-specific emission rates of VOCs from building products, must include the following key components: an emission cell, a clean air generation and humidification system, and monitoring and control systems (to ensure that the test is carried out according to specified conditions). Sample tubes are also required (usually packed with Tenax®). Note that the analysis of VOCs collected from emission cells can be carried out remotely.

For rigid (non-compressible) materials or products with a smooth planar surface, the FLEC is placed directly onto the surface of the test specimen. Compressible or textured products require specially constructed test specimen holders¹².

The emission cell itself and all parts of the sampling system that come into contact with emitted VOCs (all tubing and couplings) are made of surface-treated (polished) stainless steel or other inert non-adsorbing/non-emitting materials. The sealing O-ring is low-absorbing and low-emitting, and outside the critical internal air volume of the cell. It is easily accessed and removed for cleaning or replacement.

Air supply and mixing facilities

The FLEC Air Flow Controller provides pure, humidified and readily controlled air to the FLEC cell. Typical inlet air flow rates range from 200 to 1400 mL/min.

Air leaks

The FLEC is operated above atmospheric pressure to avoid any influence from the laboratory atmosphere. This is achieved by ensuring that the sum of the pump sampling flows is typically set at 75–80% of the inlet flow rate. The excess air exits through an exhaust vent.

The system is tested for air leaks by comparing the inlet air flow with the sum of the outlet flows (sorbent tubes plus exhaust). These are required to differ by less than 10% in most standard methods.

Indoor materials/products permeable to air require air-tight test specimen holders or air-tight, inert base plates to avoid permeation of air through the sample.

Air sampling

Air is sampled by connecting conditioned sorbent tubes to either or both of the tube outlet couplings on FLEC. As above, the sum of sampling air flows is usually set to 75–80% of the inlet flow¹³.

Recovery and sink effects

The recovery of toluene, n-dodecane and target VOCs, as required by most standard methods, is determined using the FLEC Test Kit for Recovery Measurements (for a detailed description, see Appendix B¹²). The concentrations of pure compound generated inside the FLEC cell using the test kit need to be of similar magnitude to those expected during the emission tests of indoor materials/products. If target analytes are very volatile, this may require the vial of standard to be capped with a ground-glass plug with a capillary hole through it, to reduce the rate of emission.

Recovery tests are typically carried out by determining the vapour concentration within the FLEC cell several times, usually over a 24–72 h period after the start of the test. This allows an average air concentration to be determined. At the end of the recovery test, the actual weight loss of the emission source is measured and combined with the inlet air flow to generate a predicted average vapour concentration for the test. Most standard methods require the actual average vapour concentration to be at least 80 or 90% of that predicted from the weight loss calculation.

Note that dehumidified air may be required for determining the recovery of hygroscopic VOCs using diffusion-controlled sources, such that weight measurements are not affected by the sorption of water.

Note also that recovery tests can be carried out over shorter periods of time (e.g. 1–24 h) for more volatile analytes.

Test specimen holders

Sample holders¹² are designed so that the weight of the emission cell is carried by the flat rim of the test specimen holder, not the material itself. Most specimen holders can be adjusted to allow the sample surface to be raised or lowered. This allows the internal volume of the FLEC to remain unaffected (relative to its volume when placed directly onto the surface of rigid products).

Preparation of samples for insertion into sample holders, in such a way as to minimise edge effects, is described in more detail later.

Equipment required for vapour sampling

- Up to five identical, capped and conditioned sample tubes containing one or more sorbents are required for each FLEC emission test:
 - One or two for collecting air samples during the background check (see later)
 - Two for air sample collection during the emissions test itself
 - One to be used as a laboratory blank

Note that a suitable internal standard (for example deuterated toluene) can be added to blank tubes prior to air sample collection if desired. Recovery of the internal standard, determined during subsequent TD-GC/MS analysis, can then be used as a check on the entire process of sample tube storage, air sample collection and analysis.

- Two calibrated constant-flow FLEC sampling pumps
- One or more calibrated air flow meters.

Cleaning the FLEC

Having first removed the sealing O-ring, the FLEC can be cleaned using one of two methods:

1. The inner surface can be washed with a diluted alkaline detergent, followed by two separate rinsings with freshly distilled water. The inner surface is then rinsed again with non-denatured ethanol or another appropriate solvent.
2. It can be cleaned by heating in a vacuum oven at elevated temperature (70–100 °C) for approximately 2 hours.

Test conditions

Test conditions must be selected to suit the applicable standard method, but are typically as follows:

- Temperature: 23 (± 2) °C
- Relative humidity (inside the emission cell): 50 (± 5)%
- Background of total VOC (sum of VOCs): below 20 µg/m³
- Background of individual/target VOCs: lower than 10% of measured emissions or below 2 µg/m³
- Surface air velocity: in the range 0.003–0.1 m/s, requiring an inlet air flow rate in the range 100–2800 mL/min. Typical inlet air flow rates are in the range 200–1400 mL/min
- Tube sampling rates: 80 mL/min (for an inlet air flow rate of 200 mL/min) to 500 mL/min (for an inlet air flow rate of 1400 mL/min).

Preparation of material samples

Detailed advice on sample selection, storage, transportation and labelling are given in relevant standard methods such as ENV 13419-3, ISO 16000-11 and ASTM WK 3368. These standard methods also describe the preparation of test specimens from the bulk samples collected from stores or manufacturers.

After preparation of a test specimen, it must immediately be put into a suitable storage area or placed under the FLEC itself. This time is regarded as the starting time of the emission test, *i.e.* $t = t_0$.

If the indoor material/product is compressible or textured and requires a sample holder, the test specimen should fit tightly inside the sample holder to eliminate edge effects. Once a sample has been placed inside a holder at time t_0 it should be stored in that specimen holder (either under the FLEC cell or in the conditioned storage area) throughout the duration of the emissions test.

If the material/product is permeable, the underside of the test specimen should be secured to a sheet of clean glass or stainless steel using non-contaminating aluminium tape.

Carrying out a material emissions test

Measuring background concentrations

A sample of the emission cell background air should be taken before the start of an emission test to quantify any background contribution of VOCs from the air supply or from the emission cell apparatus itself. This is done by placing the FLEC, complete with its sealing O-ring, on a clean planar surface (*e.g.* a glass or stainless steel plate). The inlet air flow should be set to that required for emissions testing and the FLEC cell flushed with clean, humidified air, to vent, for approximately 15 minutes. One or two conditioned sorbent tube/pump assemblies should then be connected to the outlet ports of the emission cell and used to sample the air for the same length of time and at the same flow rate as will be used for sample collection. The levels of analytes found in the background air can then be determined using a calibrated TD-GC/MS system (methods: ASTM D6196, ISO 16000-6 or ISO 16017-1).

Preparing for air sample collection

If the indoor material/product to be tested is not to be stored under the emission cell, it must be placed (or replaced) under the emission cell:

- at least 15 minutes prior to air sample collection (in the case of most dry materials/products)
- or
- at least 2 hours prior to air sample collection (whenever the test specimen is a dried/cured coating or target compounds include highly polar species).

Note that several standard methods require the sample to be replaced under the test cell 24 hours before emissions are measured.

The supply of clean humidified air must be turned on as soon as the FLEC is placed onto the sample.

Typical inlet air flows range from 200–1400 mL/min. The inlet air flow rate will affect the air velocity at the surface of the sample – see Appendix A for calculating approximate surface air velocities from the inlet air flow rate. Generally speaking, the inlet air flow rate and related surface air velocity are not critical for emissions from dry products – *i.e.* those controlled by internal diffusion within the product.

After the sample has been allowed to ‘equilibrate’ under the FLEC cell for the required time, two conditioned and calibrated sample tube–pump assemblies should be connected to the outlet ports of the emission cell. When the pumps are switched on, this marks the beginning of air sample collection. Check for leak tightness (as described above) as quickly as possible, at the beginning of air sample collection.

Pumped sampling flows typically vary from 80–500 mL/min. These flows are within the optimum range for short-term sampling on standard sorbent tubes. The pump flows should be set so that the sum of the sampling flows is 75–80% of the total inlet air flow. For example, an inlet air flow rate of 500 mL/min would normally be used with pump flow rates of 200 mL/min through each of the two sorbent tubes.

Timing of emissions measurements

Emissions measurements can be made at any time after sample preparation, and will depend on test objectives and the requirements of standard methods. Typical sample collection times are 2 hours, 24 hours, 72 hours, 10 days, 28 days, 56 days and 182 days (26 weeks) after preparation of the sample at time t_0 . Note that the mid-point of the period of air sample collection is considered the actual sampling time. As mentioned above, between tests, samples must either be stored under the FLEC cell itself or in suitable (clean, well-ventilated) storage areas under appropriate conditions of humidity and temperature.

Air sample collection

Two air samples should be collected by attaching a pair of identical sorbent tube–pump assemblies to the FLEC. Typical air sample collection periods for general VOCs range from 15 minutes to 2 hours. Different pump flow rates within the 80–500 mL/min range can be used to sample onto each of the two sample tubes attached to the emission cell, provided that the actual period of sample collection is the same. As soon as the pumps are switched off at the end of sampling, the sorbent tubes should be disconnected and sealed with long-term storage caps as specified in TD standard methods. The tubes can then be sent for TD–GC/MS or TD–GC/FID analysis. Most standard methods require that the vapour concentration data, determined from analysis of each of the tubes, agrees within certain limits – typically within 10%.

Note that the FLEC should normally be cleaned before it is used for another test.

Calculation of area-specific emission rates and expression of results

Area-specific emission rates (SER_a values) can be calculated from experimental parameters and data. These are as follows:

A	Exposed sample surface area [in cm^2] = 177 cm^2 in the case of FLEC
M_1 and M_2	Mass of each target VOC retained by the first and second sample tubes respectively [in μg]. This is determined using a calibrated TD–GC/MS or FID analytical system and following D-6196, ISO/DIS 16000-6, ISO 16017-1 or equivalent.
F	Flow rate of pure, humidified air into the cell [in $cm^3/min = (m^3/h \times 10^5)/6$]
F_1 and F_2	Pump air flow rates through the first and second sample tubes respectively [in $cm^3/min = (m^3/h \times 10^5)/6$]
τ	Duration of test [in minutes]
V	Volume of air [in cm^3] passed into the cell during the emission test = $F \times \tau$
V_1 and V_2	Volumes of air [in cm^3] pumped through the first and second sample tube respectively = $F_1 \times \tau$ and $F_2 \times \tau$ respectively
C_x	Concentration of vapour of component x within the emission cell [in $ng/cm^3 = \mu g/m^3 \times 10^{-3}$] = mean of that determined from sample tube 1 (M_1/V_1) and that determined from sample tube 2 (M_2/V_2)

Assuming negligible background of each target VOC, the area-specific emission rate, SER_a , for component x can be derived from these parameters as follows:

The mass of x (in μg) emitted by the exposed area of sample during the emissions test is:

$$M_x = C_x V \quad (1)$$

The mass of x (in μg) emitted by the exposed area of sample per hour is obtained by multiplying M_x by 60 and dividing by the actual duration of the test in minutes:

$$M_x \times \frac{60}{\tau} \quad (2)$$

To derive the area-specific emission rate, at time t, in $\mu g/m^2/h$, we multiply the result from equation (2) by 10^4 and divide by the exposed sample surface area (177 cm^2):

$$SER_a = M_x \times \frac{60}{\tau} \times \frac{10^4}{177} \quad (3)$$

Background correction of SER_a data

To correct for background concentrations of a VOC, x, derive the effective area-specific emission rate ($\mu g/m^2/h$) for the blank emission test and subtract this from the experimentally derived area-specific emission rate for the test specimen. Note, however, that high background concentrations of target VOCs will invalidate the emissions test.

Deriving units for comparison with small-chamber emission tests

- L Surface area [in m^2] of test specimen exposed in the cell divided by cell volume [in m^3]
 n Air change rate (changes per hour)
 = air flow rate entering the cell [in cm^3/h] divided by the cell volume [in cm^3]
 q Area-specific air flow rate = n/L

Deriving SER_a using analogous methods to those used for small-chamber emissions tests

At a given test condition, C_x depends on the area-specific emission rate of the test specimen and the air flow rate through the emission test cell. For individual VOCs, the compounds found both in the material and in the background should be subtracted compound by compound; for TVOC, the measured background should be subtracted. The relation between C_x , the area-specific emission rate (SER_a) and the area-specific air flow rate (q) of the emission test cell can be expressed as:

$$C_x = \frac{SER_a \times L}{n} = \frac{SER_a}{q} \quad (4)$$

Equation (4) shows that the area-specific air flow rate equals the n/L ratio. For a given product tested under given emission test cell conditions, the concentration of a specific VOC depends on the area-specific air flow rate.

C_x is the mean concentration of x calculated from the duplicate air samples as described above.

$$\text{At time } t, \quad SER_a = C_x \times q \quad (5)$$

Reporting SER_a results

Test results should be related to the time of the emission measurement after t_0 and should be reported quantitatively as the area-specific emission rate, of individual VOCs and/or TVOC at time t .

Note that the sum of individual emitted VOCs (TVOC) should only be regarded as a factor specific to the product studied and to the monitoring method used. It is therefore only to be used for comparison of products with similar target VOC profiles if exactly the same test method has been used for each comparative measurement.

References and notes

- For examples, see Application Notes TDTS 9 (general), TDTS 57 (paint) and TDTS 59 (car trim components).
- P. Wolkoff *et al.*, Field and Laboratory Emission Cell: FLEC, Proceedings of Healthy Buildings '91, 1991, pp. 160–165.
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- E. Uhde *et al.*, Characterisation of the FLEC: Flow field and air velocities, *Atmospheric Environment*, 1998, 32: 773–781.
- S. Murakami *et al.*, 3D-CFD analysis of diffusion and emission of VOCs in a FLEC cavity, Proceedings of the 9th International Conference on Indoor Air Quality and Climate, *Indoor Air*, 2002, 2: 548–552.
- Z. Guo, B. A. Tichenor, K.A. Krebs and N.F. Roache, Considerations on revisions of emissions testing protocols, in: *Characterising sources of indoor air pollution and related sink effects*, ed. B. Tichenor, 1996, 225–236.
- Note that surface air velocity has very little effect on emissions controlled by internal diffusion (dry samples), but is critical for wet samples, where the primary emission process is evaporation (external diffusion). In the case of evaporative emissions, while it remains possible to compare emission data from wet samples collected using the FLEC under identical conditions, the non-uniformity and relative slowness of the air velocity at the surface of the sample make it difficult to compare FLEC data with that obtained for the same sample using emission chambers. Note also that similar limitations make it difficult to compare emission data for wet samples from two different small chambers or from the same chamber under different operating conditions.
- See also Application Note TDTS 72.
- T.G. Matthews, C.V. Thompson, D.L. Wilson and A.R. Hawthorne, Air velocities inside domestic environments: an important parameter in the study of indoor air quality and climate, *Environment International*, 1989, 15: 545–550.
- J.R. Girman, Simple modeling to determine appropriate operating conditions for emission testing in small chambers, in: *Modeling of indoor air quality and exposure*, ed. N. L. Nagda, 1993, pp. 145–148.
- K. Kovanen, O. Seppänen and A. Majanen, Turbulent air flow measurements in ventilated spaces, *Indoor Air '87*, Berlin, 1987, 3: 329–333.
- See Markes' Accessories & Consumables Catalogue for more information.
- See relevant standard methods for choice of sorbent or guidance on sorbent selection. Alternatively, refer to Application Notes TDTS 5 and TDTS 20.

Trademarks

FLEC® is a registered trademark of Chematec, Denmark.

Tenax® is a registered trademark of Buchem B.V., The Netherlands.

Appendix A: Estimation of air velocity at the surface of a test specimen in an emission cell

Actual air velocities within an emission cell under different air flow conditions can be studied using three-dimensional computational fluid dynamics. An estimation of mean air velocity at the test specimen surface can also be made based on FLEC dimensions as follows:

Air enters the FLEC through a baffle around the perimeter (radius 7.5 cm) and exits through a single point located centrally and immediately above the test specimen surface. The volume of this cell is 35 cm³. This means that if air was flowing into the cell at 35 cm³/min, it would take approximately 1 minute to pass from the inlet to the outlet of the cell, and the mean air velocity over the surface of the test specimen would therefore be approximately 7.5 cm/min. This equates to 1.25×10^{-3} m/s.

At an inlet air flow rate of 140 cm³/min (which is near to the lower limit of inlet air flow), this means that the average air velocity over the surface of the test specimen would be approximately 0.005 m/s.

Similarly, at 350 cm³/min (a typical inlet air flow), the air velocity over the surface of the test specimen would be approximately 0.0125 cm/s.

At 1400 cm³/min, the mean air velocity over the surface of the test specimen would be in the order of 0.05 cm/s.

At 2800 cm³/min (a high inlet air flow), the mean air velocity over the surface of the test specimen would be in the order of 0.1 cm/s.

Note that mean air velocities in the domestic indoor air environment are in the order of 0.07 m/s ¹.

Appendix B: Example apparatus for recovery measurements

The apparatus comprises:

- A glass plate with precision-ground hole in the middle
- A small (typically 2 mL) glass vial with a precision-ground-glass neck (to exactly fit the hole in the plate)
- An insulating pad with a central hole to locate the bottom of the glass vial.

To carry out a recovery test, a volume of the compound of interest is placed in the vial and weighed. The vial is then fitted into the plate, which is placed on the insulating cushion so that the bottom of the vial locates with the hole in the pad. The FLEC cell is then placed centrally onto the glass plate with the inlet air flow applied, and emissions measurements are made as described in the main text.

The vial is weighed at the end of the recovery test and the weight loss used to calculate an expected average vapour concentration in the cell throughout the recovery test. This is then compared with the measured vapour concentration to assess recovery.