International Standard

ISO 27548

Additive manufacturing of plastics — Environment, health, and safety — Test method for determination of particle and chemical emission rates from desktop material extrusion 3D printer

Fabrication additive de plastiques — Environnement, santé et sécurité — Méthode d'essai pour la détermination des taux d'émission de particules et de produits chimiques des imprimantes 3D de bureau par extrusion de matériau

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 261, *Additive manufacturing*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 438, Additive manufacturing, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Academic communities have been releasing several papers warning that a significant number of particles and chemical substances emitted from material extrusion (MEX) AM processes commonly used in schools, private homes and similar non-industrial environments would be hazardous to humans when inhaled and absorbed into the human body.

However, currently, there is no well-known test method to measure particle and chemical substances emitted from desktop MEX-TRB/P machines, commonly called "3D printers" installed in the office environment, classroom, and residential space.

Therefore, the goal of this document is to provide test procedures in line with specific operating conditions for measuring particle and chemical emission rates emitted from desktop MEXTRB/P machine, also known as a 3D printer which is widely used in the national marketplace.

Manufacturers of desktop MEX-TRB/P machines, also known as 3D printers, will be able to take advantage of this document to develop and improve their products by minimizing particle and chemical emission rates, and the end-users also would purchase more safe and improved machines from the market.

Additive manufacturing of plastics — Environment, health, and safety — Test method for determination of particle and chemical emission rates from desktop material extrusion 3D printer

1 Scope

This document specifies test methods to determine particle emissions (including ultrafine particles) and specified volatile organic compounds (including aldehydes) from desktop MEX-TRB/P processes often used in non-industrial environments such as school, homes and office spaces in an emission test chamber under specified test conditions. However, these tests do not necessarily accurately predict real-world results.

This document specifies a conditioning method using an emission test chamber with controlled temperature, humidity, air exchange rate, air velocity, and procedures for monitoring, storage, analysis, calculation, and reporting of emission rates.

This document is intended to cover desktop MEX-TRB/P machine which is typically sized for placement on a desktop, used in non-industrial places like school, home and office space. The primary purpose of this document is to quantify particle and chemical emission rates from desktop MEX-TRB/P machine.

However, not all possible emissions are covered by this method. Many feedstocks can release hazardous emissions that are not measured by the chemical detectors prescribed in this document. It is the responsibility of the user to understand the material being extruded and the potential chemical emissions. An example is Poly Vinyl Chloride feedstocks that can potentially emit chlorinated compounds, which cannot be measured by the method described in this document.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 554, *Standard atmospheres for conditioning and/or testing — Specifications*

ISO 16000-3, *Indoor air — Part 3: Determination of formaldehyde and other carbonyl compounds in indoor and test chamber air — Active sampling method*

ISO 16000-6, *Indoor air — Part 6: Determination of organic compounds (VVOC, VOC, SVOC) in indoor and test chamber air by active sampling on sorbent tubes, thermal desorption and gas chromatography using MS or MS FID*

ISO 16000-9, *Indoor air — Part 9: Determination of the emission of volatile organic compounds from building products and furnishing — Emission test chamber method*

ISO 27891, *Aerosol particle number concentration — Calibration of condensation particle counters*

ISO/IEC 28360-1:2021, *Information technology — Determination of chemical emission rates from electronic equipment — Part 1: Using consumables*

ISO/ASTM 52900, *Additive manufacturing — General principles — Fundamentals and vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/ASTM 52900, ISO/IEC 28360-1 and the following are applied.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
loading factor
ratio of the device volume to the volume of the unloaded Emission Test Chamber

Note 1 to entry: For the purpose of this standard, the device subjected to the testing is typically a desktop MEX-TRB/P machine, also popularly called a 3D printer

[SOURCE: ISO/IEC 28360-1:2021, 4.18, modified — “EUT” replaced by “device” and Note 1 to entry added.]

3.2
emission test chamber
ETC
enclosure with controlled operational parameters for the determination of chemical compounds and amount of particles emitted during the process

Note 1 to entry: For determining the emissions from AM process, typical controlled parameters include, but are not limited to, temperature, humidity, air exchange rate, and others

[SOURCE: ISO 16000-9:2006, 3.6, modified — Terminological entry is changed considering AM process]

3.3
differential electrical mobility classifier
DEMC
classifier able to select aerosol particles according to their electrical mobility and pass them to its exit

Note 1 to entry: A DEMC classifies aerosol particles by balancing the electrical force on each particle with its aerodynamic drag force in an electrical field. Classified particles are in a narrow range of electrical mobility determined by the operating conditions and physical dimensions of the DEMC, while they can have different sizes due to difference in the number of charges that they have.

Note 2 to entry: Another common acronym for the DEMC is DMA.

[SOURCE: ISO 15900:2020, 3.11]

3.4
differential mobility analysing system
DMAS
system to measure the size distribution of submicrometre aerosol particles consisting of a charge conditioner, a DEMC, flow meters, a particle detector, interconnecting plumbing, a computer and suitable software

Note 1 to entry: Another common acronym for the DMAS is MPSS (mobility particle size spectrometer).

[SOURCE: ISO 15900:2020, 3.12]

3.5
light scattering airborne particle counter
LSAPC
instrument capable of counting and sizing single airborne particles and reporting size data in terms of equivalent optical diameter

Note 1 to entry: The specifications for the LSAPC are given in ISO 21501-4:2007.

[SOURCE: ISO 14644-1:2015, 3.5.1]

3.6
accumulated particle number concentration
C_p
time-dependent number for the concentration of particles in a specified size range

3.7
total particles
number of particles as calculated based on the measured *accumulated particle number concentration* (3.6) in the sampled volume and the duration of the particle emission test

3.8
particle emission rate
PER
particles emitted from AM process per unit time (1/h) in a specified size range that is calculated from *accumulated particle number concentration* (3.6) divided by the build time in h

3.9
particle emission yield
$Y_{particle}$
number of particles emitted per mass of extruded material during the build cycle

3.10
chemical emission yield
$Y_{chemical}$
mass of chemical compounds emitted per mass of extruded material during the build cycle

3.11
chemical emission rate
average mass of organic compounds emitted from an AM process per unit of time

3.12
toluene response factor
toluene equivalents used to quantify the unidentified substances detected with a flame ionization detector (GC-FID) or mass spectrometric detector (GC-MS)

3.13
total volatile organic compounds
TVOC
sum of the concentrations of identified and unidentified volatile organic compounds eluting between and including n-hexane and n-hexadecane.

Note 1 to entry: For a MEX-TRB/P-process, the total volatile organic compounds are typically measured using a non-polar capillary GC column and the concentrations of the converted areas of unidentified peaks using the toluene response factor

[SOURCE: ISO 16000-9:2024, 3.14, modified — Note 1 to entry rewritten and Note 2 to entry deleted.]

4 Abbreviated terms and symbols

4.1 Abbreviated terms

ABS	Acrylonitrile butadience styrene
CPC	Condensation particle counter
DNPH	Dinitrophenylhydrazine
FP	Fine particles
GC/MS	Gas chromatography/mass spectrometry
HPLC	High performance liquid chromatography
PLA	Poly lactic acid
RH	Relative humidity
RPD	Relative percentage difference
RSD	Relative standard deviation
TP	Total particles
UFP	Ultrafine particles

4.2 Symbols

β	particle loss-rate coefficient (h^{-1})
C_{av}	arithmetic average of $C_p(t)$ between t_{start} and t_{stop} (cm^{-3})
C	VOC concentration during the extrusion phase ($\mu g \cdot cm^{-3}$)
C_b	VOC concentration during the pre-extruding phase ($\mu g \cdot cm^{-3}$)
L	loading factor ($m^3 \cdot m^{-3}$)
PER(t) [$r_{pe}(t)$]	time-dependent particle emission rate (s^{-1})
PER_h ($r_{pe,h}$)	particle emission rate for an average hour (h^{-1})
Δt	time difference between two successive data points (s)
t_{start}	time when print command sent (s)
t_{stop}	time when extrusion ends (s)
r	air exchange rate (h^{-1})
P_m	final test specimen mass after extrusion completes (g)
V_c	emission test chamber volume (m^3)
V_s	sample volume during the extruding phase (m^3)

5 Method overview

This document specifies test methods to determine particle and chemical emission rates during the operation of the desktop MEX-TRB/P machine. Particle and chemical emissions are determined by the chamber concentration emitted from the operation of the desktop MEX-TRB/P machine inside an ETC where temperature, humidity, air exchange rate, and air velocity are controlled. Test procedures are divided into three phases: pre-extruding, extruding and post-extruding.

The observed chamber concentration during the extruding phase is converted to the particle emission rate per hour or used material mass by mathematical calculations. The procedures for the build conditions should be under the standard operating conditions (see A.2) of the desktop MEX-TRB/P machine. Chemical emissions (TVOC and aldehydes) are directly calculated from the chamber concentration as mass per hour.

There are various reasons for performing these measurements. For example, determining the maximum emissions for using machines or comparing emissions from different AM machines. The procedures used for the test can be tailored for the specific purpose of the test. In the case of determining maximum emission rates, the AM machine should be set at the conditions that result in maximum emissions, which are typically the fastest extruding speed, the thickest layer, and the highest nozzle temperature recommended by the manufacturer. For comparing emission rates from different AM machines, the process settings shall be referred to values that are outlined in Annex A.

6 Requirements of the instrument for measurement

6.1 General

6.1.1 Emission test chamber (ETC)

The ETC shall be designed with stainless steel electropolished materials so that it does not emit or absorb substances that can affect measurements during background and AM process tests. During operation, the ETC shall be controlled for constant temperature, humidity, and air exchange rate (see 7.1), and they shall be continuously monitored by using data logging instruments that are calibrated and traceable to primary standards.

General requirements for other materials comprising of an air supply system, mixing equipment and air tightness which are used to construct ETC shall be tested in the ETC to confirm that they do not contribute to the emission test chamber background concentration through emission or adsorption. The test setup of ETC shall not recirculate chamber air so as not to have the contaminated air put into the ETC again.

When flow changes are made to chamber air, a tracer gas test shall be performed to confirm the accuracy of the air exchange rate. The verification process for the test conditions of the ETC such as a tracer gas test procedure and a recovery test shall be performed in accordance with ISO 16000-9 or ASTM D6670.

6.1.2 Instruments for chemical analyses

VOC emitted from MEX operation inside the ETC shall be analysed by thermal desorption GC/MS with the use of a sorbent like Tenax TA®[1)] or a multi-bed tube as the one consisting of Tenax® GR plus Carbopack™B[2)]. The multi-bed tube Tenex/Carbopack consists of 30 mm Tenax® GR plus 25 mm of Carbopack™B separated by 3 mm of preconditioned quartz wool, or one having in equal performance. These are commercially available prepacked and preconditioned if required.

An electron impact instrument (EI) of GC/MS shall be operated in the scanning mode over a mass range of at least *m*/*z* 35-350. The general analytical method for the emission of VOC from MEX AM machine using ETC shall be based on ISO 16000-6, EPA Method TO-17, and ASTM D6196.

1) Tenax ® TA is a trademark of *"Tenax international B.V"*. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of the product named.

2) Carbopack™B is a trademark of *"Supelco"*. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of the product named.

Benzaldehyde, phenol, and acetophenone are some of the known artifacts present when sampling using Tenax tubes. Therefore, Tenax TA® should be used with an ozone scrubber to avoid chemical artifact formations to be formed via oxidation when sampling under high ozone concentrations. The method and precautions related to GC/MS using a sorbent tube should be based on ISO 16000-6 and EPAF TO-17.

The formaldehyde and other carbonyl compounds which are collected from cartridges with 2,4-dinitrophenylhydrazine with an ozone scrubber shall be analyzed by HPLC with detection by ultraviolet absorption. Formaldehyde, acetaldehyde, acetone, acrolein, propionaldehyde, crotonaldehyde, benzaldehyde and *o*-, *m*-, *p*-tolualdehydes shall be identified.

The general analytical method for determination of aldehydes concentration shall be based on ISO 16000-3 and ASTM D6007. Especially, the limitations and interferences concerning the determination of organic substances can be referred to in ISO 16000-3:2022, Clause 5. If a peak of acrolein on the chromatogram of DNPH-formaldehyde derivative is of multiple formation and instability, it shall be quantified by using the test method EPA TO-11A.

The digital scale used for weighing the printed object shall have at least a 0,01 g sensitivity. The object including supports shall be weighed after placing at the constant controlled temperature and humidity mentioned in 7.1.

6.1.3 Aerosol instruments

Aerosol instruments shall be able to measure total particle number concentration over time with particle size ranging below 3 000 nm and classify particles by size.

An aerosol instrument shall use CPC and/or a combination of DMAS and LSAPC widely known as an optical particle counter. In the case of the combination of aerosol instruments, consistency between the two different aerosol measurement instruments shall be checked.

The DMAS should be capable of counting particle size range from at least 7 nm to at least 300 nm and LSAPC should measure particle number distribution for particle optical diameter of 300 nm to at least 3 000 nm. The DMAS detection efficiency at the lower size limit (7 nm) shall be equal or higher than 50 %.

The lower and upper limits of the concentration range of particles required for the CPC used shall be realized 1 cm^{-3} to 10^7 cm^{-3}. The calibration for the counting efficiency of the CPC shall comply with ISO 27891.

The operational readiness test for aerosol measuring system shall be passed prior to testing as specified in ISO/IEC 28360-1:2021, Annex B.

6.2 General requirements of desktop MEX-TRB/P machine and test specimen

6.2.1 Desktop MEX-TRB/P machine

The desktop MEX-TRB/P machine before test preparation shall be kept in place at the constant controlled temperature and humidity given in 7.1. The packed desktop MEX-TRB/P machine shall be removed from all packing provided by the manufacturer before a test and shall be tested as soon as possible within 24 h. The exposure time of the unpacked desktop MEX-TRB/P machine in the conditioning environment shall be recorded.

When a thermoplastic filament is forced through the extrusion nozzle during setup of the desktop MEX-TRB/P machine, any burnt filament attached around the outside of the nozzle shall be cleaned out with acetone or ethyl alcohol once the nozzle has cooled. These chemicals used for cleaning residues shall be fully evaporated before loading the desktop MEX-TRB/P machine into the ETC.

6.2.2 Filament

The feedstock filament supplied by the manufacturer shall be stored as recommended by the filament manufacturer and it shall be unpacked as soon as possible before testing within 24 h and loaded into the nozzle. The exposure time of the unpacked filament in the conditioning environment shall be recorded. Once the filament is loaded into the nozzle of desktop MEX-TRB/P machine, it shall not be replaced by other types of filaments. The mass of the used filament (i.e. the finished test specimen including support) shall be weighed to 0,01 g. The test specimen is placed in a desiccator and allowed to dry once 1 h until the weight difference of the dried test specimen is less than 1 %.

The information on the filament and desktop MEX-TRB/P machine used for printing a test specimen shall be recorded according to 9.2 to inform the history on which it is originated.

6.2.3 Test specimen

The model of this test specimen has a size of 70 mm × 70 mm × 15,4 mm. Each feature of the test specimen shall be built as the specified artifact of Annex B. The total build time can be adjusted to build over 4 h based on the conditions recommended by the manufacturer depending on the standard operating conditions specified in Table A.1. The build time shall be adjusted to build more than 4 h using the manufacturer's recommended standard operating conditions such as printing speed, layer thickness, filling percentages (density), etc.

The test specimen (see Figure 1) below is comprised of several features with simple geometry on the square-shaped base. There are 5 different shapes with positive and negative features from the surface such as positive and negative rectangular blocks of different sizes, octangular tower, different font types. This specimen is intended to measure particle and chemical emission rates during the operation of a desktop MEX AM machine, but not to test the accuracy of the test specimen.

The 3D digital model for a test specimen can be downloaded in STL file format by clicking on the link in Annex B in the digital copy of this document.

The features of the test specimen shall be as shown in Annex B.

Dimensions in millimetres

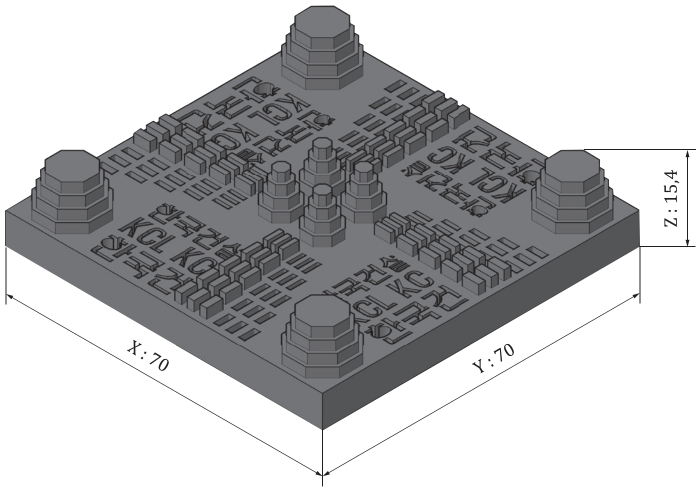


Figure 1 — Test specimen

7 ETC conditions and test procedures

7.1 ETC general conditions

The appropriate chamber size depending on the volume of the desktop MEX-TRB/P machine is selected based on the criterion for the loading factor in Formula (1):

$$0{,}01 < \frac{V_{AM}}{V_c} < 0{,}25 \quad (1)$$

where

V_{AM} is the volume of the desktop MEX AM machine, in m^3;

V_c is the volume of the emission test chamber, in m^3.

If a desktop MEX-TRB/P machine is planned for the floor-mounted systems as used in non-industrial purposes and satisfied with the qualification of Formula (1), this test method is able to apply to the general MEX-TRB/P machines. The Volume VAM should be measured by the assembled three longest sides of the desktop MEX-TRB/P machine.

For the ETC, emission tests shall be executed at 23 °C and 50 % RH in accordance with ISO 554. The test chamber shall be able to control the temperature and humidity within the below condition ranges for the duration of pre-extruding, extruding and post-extruding.

a) Temperature : 23 °C ± 2 °C

b) Humidity : 50 % ± 5 % RH

c) Air velocity : 0,1 m/s to 0,3 m/s

d) Air exchange rate: $n \cdot h^{-1}$

Air velocity shall be measured at a spot 15 cm above the desktop MEX-TRB/P machine, in the middle of the machine with respect to length and width, and measured in the direction parallel to the floor of the ETC and perpendicular to the side of the ETC where the airflow enters.

With an ETC volume of 5 m^3 or larger, the air exchange rate of the ETC shall be in the range of (0,5 to 2,0) h^{-1}, while a volume smaller than 5 m^3 shall be in the range of (0,5 to 5,0) h^{-1}.

7.2 ETC background concentration

For the unloaded test chamber, the background concentration of particles shall be less than 100 cm^{-3} when the air exchange rate is $n = 1 \cdot h^{-1}$. The requirements of concentration shall be confirmed including particle size ranging below 300 nm by using the aerosol instruments specified in 6.1.3. TVOC shall be lower than 20 μg/m^3 and the concentration of each target VOC species and aldehydes shall be lower than 2 μg/m^3.

7.3 Preparation of ETC and desktop 3D printer

The desktop MEX-TRB/P machine and filament shall be stored in an air-conditioned room (23 °C, 50 % RH) in its original packaging prior to the test. The test shall be initiated within 24 h following unpacking the desktop MEX-TRB/P machine and filament.

The ETC interior walls shall be cleaned with an alkaline detergent and rinsed with distilled water as described in ISO 16000-9, followed by cleaning with fresh air whose volume is equivalent to at least 4 times that of the interior capacity to meet the requirements specified in 7.2

A desktop MEX-TRB/P machine following the requirements specified in 6.2.1 shall be installed at the center of the ETC with respect to the length and width of the ETC, at a height of 1 m to 1,5 m from the floor. A computer, including desktop MEX-TRB/P machine control software, shall be connected from outside the ETC to the internal desktop MEX-TRB/P machine. All particle and chemical sampling lines shall be made of conductive material to minimize losses of the particle due to static electricity. The sampling lines shall be cleaned regularly before and after the test.

The position of the aerosol and chemical sampler ports shall be at least 10 cm away from the inner chamber wall and at least 30 cm away from the desktop 3D printer. The length of the sampling lines from the outer chamber wall should be minimized (within a maximum length of 3 m) and installed without sharp bends.

The desktop MEX-TRB/P machine and all auxiliary equipment should be wiped down or vacuumed to remove any dust or dirt. After setting up the desktop MEX-TRB/P machine, filament and all auxiliary equipment for operation inside the ETC, desktop 3D printer shall be conditioned with clean air at the controlled environment until the ETC background concentrations meet the requirements specified in 7.2.

A schematic diagram of the test system is shown in Figure 2.

7.4 Pre-extruding phase

Pre-extruding phase is the preparation phase in which a desktop 3D printer is connected to an electrical supply inside the ETC, where the desktop MEX-TRB/P machine is just in the ON setting. The build platform and nozzle warming-up are the status of waiting to start.

Prior to extrusion, the desktop MEX-TRB/P machine shall be power-connected and controlled from outside of the ETC, and air exchange for the ETC shall be continued to keep the number concentration of particles, TVOC, individual VOC, and aldehyde concentrations inside the ETC lower than background. Ensure pre-extruding begins at least 1 h to 2 h prior to extruding, to allow time to perform the sampling required by 7.7.2. Aerosol Measurement instruments shall be recorded from the pre-extruding phase to the post-extruding phase.

7.5 Extruding phase

The extrusion phase is the operation phase in which the desktop MEX-TRB/P machine inside the ETC begins to operate and the material is extruded into a three-dimensional shape.

Enter the extruding phase by placing a printing order from the PC connected with the desktop MEX-TRB/P machine and increasing the temperature of the nozzle head and printing bed plate. The extruding phase ends with the final test specimen being completely manufactured. The total printing time and process parameters of the desktop MEX-TRB/P machine software during a build cycle shall be reported.

7.6 Post-extruding phase

Post-extruding phase is the end phase in which additive manufacturing has already been completed. The post-extruding phase starts at the end of the extruding phase, and the air exchange rate shall continue for at least one air exchange, and until aerosol levels return to their pre-testing background levels.

7.7 Sampling for particles and chemical substances

7.7.1 Particles

FP and UFP measurements shall be counted and recorded from the start of the pre-extruding phase through the end of the post-extruding phase.

7.7.2 Chemical substances

The samplings of VOC and aldehydes from the ETC shall be collected twice each, at the same time, in the following phases:

a) Pre-extruding phase.

The sampling of background concentration from the desktop MEX-TRB/P machine inside the ETC shall be taken during the pre-extruding phase at least 1 h before extrusion starts. The sampling amount is collected within 1 h with a sample flow of 100 ml/min to 200 ml/min. Sampling time and the amount shall be determined by chemical concentration emitted from the desktop 3D printer. Sampling and analysis procedures for VOC and aldehydes shall be performed in accordance with ISO 16000-3 and ISO 16000-6.

b) Extruding phase.

The sampling for VOC and aldehydes during the extruding phase shall last for 1 h until the post-extruding phase starts. The sampling method is the same as the pre-extruding phase.

For the pre-extruding and extruding phase, flow rates of the sampling instrument for collecting VOC and aldehydes shall be adjusted with calibrated mass flow controllers before sampling, and the mass flow meters used in calibration shall maintain uncertainty of measurement within ±2 %.

7.8 Measurement process

The desktop MEX-TRB/P machine unit is ready after measuring the background concentration inside the ETC. The following processes shall be executed in sequence:

a) After checking the background of the unloaded chamber according to 7.2, the desktop 3D printer unit shall be installed in the middle of the ETC with respect to the length and width of the ETC, at a height of 1,0 m to 1,5 m from the floor (see Figure 2);

b) The loaded chamber as part of the pre-extruding phase shall be conditioned to keep the number concentration of particles, TVOC, individual VOC, and aldehyde concentrations lower than background;

c) The sampling of VOCs and aldehyde background concentration of the loaded chamber after confirmed step 2 shall be taken during the pre-extruding phase at least 1 h before extrusion starts, and aerosol concentration shall be measured throughout the pre-extruding phase;

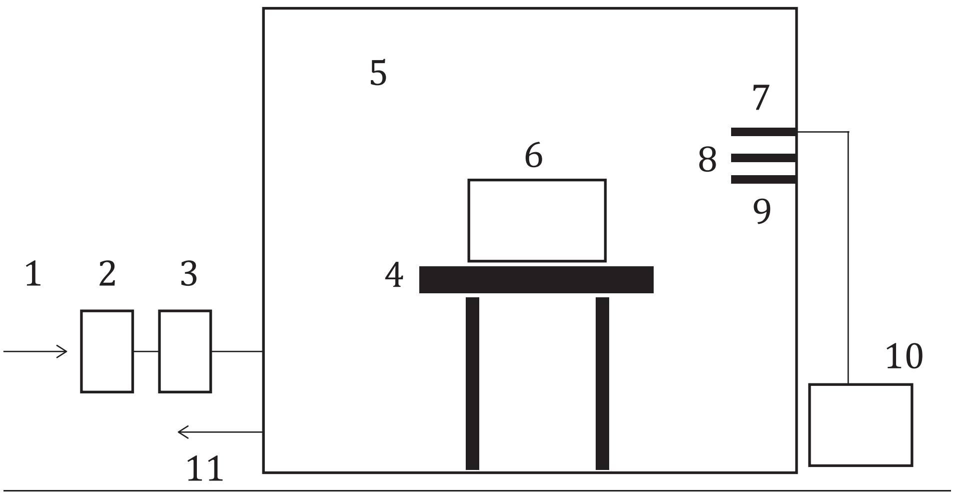
d) Test conditions of desktop MEX-TRB/P machine shall be adjusted to the standard operating conditions in Table A.1;

e) The start of the desktop MEX-TRB/P machine operation is performed when power is supplied, and the ETC background concentration is met;

f) Particles (FP & UFP) are measured during the pre-extruding, extruding and post-extruding phases, and VOC and aldehydes are collected at 1 h before post-extruding phase;

g) The VOC and aldehydes are collected according to 7.7.2 and analysed using the instruments indicated in 6.1.2;

h) Total particle number concentration is presented as a diagram of $C_p(t)/(\text{cm}^{-3})$ versus time comprising the period from the pre-extruding phase to at least 1 air exchange after the extruding phase end-point and until aerosol levels return to pretesting background levels (see Figure 3).



Key

1 air entrance
2 air purification equipment
3 air flow controller
4 stainless steel table
5 ETC
6 desktop MEX-TRB/P machine

7 aerosol sample collection tube

8 VOCs sample collection tube

9 aldehyde sample collection tube

10 aerosol equipment

11 air exhaust

Figure 2 — Schematic diagram of test system using test chamber

As shown in Figure 2, a desktop MEX-TRB/P machine shall be placed on the stainless steel table and installed at a 1,0 m to 1,5 m height from the floor in the middle of ETC. To ensure constant mixing of the air inside the ETC, the ETC system shall include an air circulation device, or be installed it inside the ETC separately. To meet the operational and general requirements for the ETC system shall be in accordance with ISO 16000-9.

8 Calculation of emission rate

8.1 Calculation of emission rate of particles

The calculation methods for particle emission rate are based on the ISO/IEC 28360-1 and RAL-UZ 205. Time-dependent particle emission rate is calculated using accumulated particle number concentration, C_p, and particle loss-rate coefficient, β, and particle emission rate per mass is calculated using material used for the three-dimensional product.

Time-dependent particle emission rate, $r_{pe}(t)$, is calculated using C_p corrected with β, as Formula (2):

$$r_{pe}(t)=V_c\left(\frac{C_p(t)-C_p(t-\Delta t)\exp(-\beta\cdot\Delta t)}{\Delta t\cdot\exp(-\beta\cdot\Delta t)}\right) \tag{2}$$

where

$C_p(t)$ is the smoothed curve of accumulated particle number concentration, in cm^{-3};

V_c is the test chamber volume, in cm^3;

Δt is the time difference between two successive data points, in s;

β is the particle loss-rate coefficient, in s^{-1}.

Where Δt is the emission time between t_{start} and t_{stop} from the diagram in Figure 3 below, where t_{start} means the time when a desktop 3D printer command sent, t_{stop} is when it stops. The unit for $r_{pe}(t)$ is s^{-1} for particle number concentration.

Total particle number, n_{TP}, shall be calculated by the integral of $r_{pe}(t)$ over the extruding phase as formulas (3), (4):

$$n_{TP}=\int_{t_{start}}^{t_{stop}} r_{pe}(t)\,\mathrm{d}t \tag{3}$$

$$n_{TP}=V_c\left(\frac{\Delta C_p}{t_{stop}-t_{start}}+\beta\cdot C_{av}\right)(t_{stop}-t_{start}) \tag{4}$$

where

C_{av} is the arithmetic average of C_p(t) between t_{start} and t_{stop} in cm^{-3};

ΔC_p is the difference of total particle number concentration of C_p between $C_p(t_{stop})$ and $C_p(t_{start})$ in cm^{-3}.

After the final test specimen is completed within the ETC, particle loss-rate coefficient (β) is calculated based on the single-exponential decay of the total particle number after printing stopped within the post-extruding phase of the diagram in Figure 3 as Formula (5):

$$\beta = \frac{\ln\left[C_p(t_1)/C_p(t_2)\right]}{t_2 - t_1} \tag{5}$$

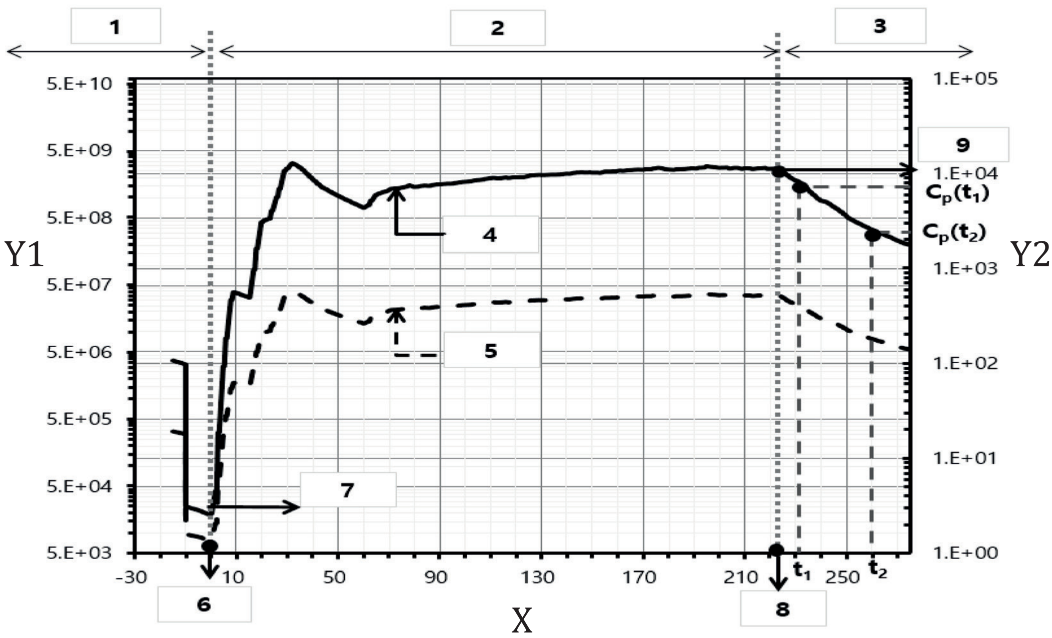
Where t_1 should be chosen at least 5 min after the end of the extruding phase and t_2 is at least 25 min after t_1.

The average time-dependent particle emission rate for 1 h, $r_{pe,h}$, and particle emission yield per mass, $Y_{particle}$, are calculated using the following Formulae (6) and (7):

$$r_{pe,h} = n_{TP} \times \frac{3\,600}{t_p} \tag{6}$$

$$Y_{particle} = \frac{n_{TP}}{P_m} \tag{7}$$

Where t_p means the extruding time during operation and shall be read in the unit (s) and P_m shall be weighed as a final test specimen (g). If the printed object has supports, they are to be weighed together to determine the total mass of filament extruded.



Key

X time (min)

Y1 $PER(t)/min^{-1}$

Y2 $C_p(t)/cm^{-3}$

1 pre-extruding phase

2 extruding phase

3 post-extruding phase

4 smoothed curve of particle number concentration, $C_p(t)$

5 particle emission rate, $PER(t)$

6 the time when a desktop 3D printer command sent, t_{start}

7 particle number concentration at the point t_{start}, $C_p(t_{start})$

8 the time when a desktop 3D printer stops extruding, t_{stop}

9 particle number concentration at the point t_{stop}, $C_p(t_{stop})$

NOTE 1 A symbol t_{start} means that it is the time when the power of the desktop 3D printer is being turned on and a print command sent and the time at the start of the bed and nozzle warm-up.

NOTE 2 A symbol t_{stop} means that it is the time when the deposition on build platform is stopped.

NOTE 3 This method requires the extruding phase to last at least 240 min, although the figure shown in this diagram ends at 220 min.

Figure 3 — Total particle number concentration and particle emission rate diagram by printing time

8.2 Calculation of volatile organic compounds emission rate

The calculation methods for chemical emission rate are based on the ISO/IEC 28360-1 and RAL-UZ 205. Chemical emission rate during the pre-extruding phase (CER_b), $R_{CE,b}$, is calculated by the following Formulae (8) and (9):

$$R_{CE,b} = C_b \cdot r \cdot V_c \tag{8}$$

$$C_b = \frac{M_{VOC,pre}}{V_s} \tag{9}$$

where:

C_b	is the VOC concentration during the pre-extruding phase, in μg·m^{-3};
$R_{CE,b}$	is the VOC emission rate during the pre-extruding phase, in μg·h^{-1};
$M_{voc,pre}$	is the analysed VOC mass during the pre-extruding phase, in μg;
r	is the air exchange rate during the pre-extruding phase, in h^{-1};
V_c	is the chamber volume in m^3;
V_s	is the sample volume during the pre-extruding phase, in m^3.

Chemical emission rate during the extruding phase (CER), R_{CE}, is calculated using the chamber concentration 1 h before the post-extruding phase and is determined by the following Formulae (10) and (11):

$$R_{CE} = \frac{c \cdot r_{ext}\, 2 \cdot V_c \cdot t_s - R_{CE,b} \cdot r_{ext} \cdot t_s}{r_{ext} \cdot t_p - e^{-r_{ext} \cdot (t_s - t_p)} + e^{-r_{ext} \cdot t_s}} \tag{10}$$

$$C = \frac{M_{VOC,ext}}{V_s} \tag{11}$$

where:

C is the VOC concentration during the extruding phase, in µg·m^{-3};

R_{CE} is the VOC emission rate during the extruding phase, in µg·h^{-1};

$M_{VOC,ext}$ is the analysed VOC mass during the extruding phase, in µg;

r_{ext} is the air exchange rate during the extruding phase, in h^{-1};

t_s is the total sampling time in h;

t_p is the total extruding time, in h.

The total VOC emission rate should be quantified by the Formula (8) to (11) of this subclause, where individual VOC and aldehydes are determined by the internal standard for the calibration and the unidentified VOC substances are quantified by the toluene response factor.

The chemical emission yield, $Y_{chemical}$, during the extrusion phase is calculated using the following Formula (12):

$$Y_{chemical} = \frac{R_{CE} \times t_p}{P_m} \tag{12}$$

where t_p means the extruding time during operation and shall be read in the unit (h) and P_m shall be weighed as a final test specimen (g) including supports.

Sum of TVOC concentration of all individual VOCs within the retention range C_6 to C_{20} should be quantified by the toluene response factor, and identified substances have to be quantified using their individual calibration standards.

9 Test report

9.1 Data on test condition and method

The following information shall be recorded for test report:

a) Date of test;

b) ETC test conditions [Temperature (T), Relative humidity (RH), Air exchange rate (r), Air velocity, in s·m^{-1}];

c) Background concentrations (record the background concentrations of particles, VOCs, and aldehydes, and the times the samples were taken);

d) Loading factor;

e) ETC volume, in m^3;

f) Location of Desktop MEX-TRB/P machine within ETC (length, width, and height with respect to the ETC);

g) ETC and environmental control system (manufacturer, model names/numbers and serial numbers of all equipment used);

h) Description of the aerosol measurement instrument used:

1) Manufacturer, model and serial number;

2) Name and version of the software;

3) Date of last factory calibration and maintenance (date, time and results of last field calibration);

4) Aerosol measuring system setting values used for measurement (count mode, sampling flow rate, reaction velocity, and etc.);

5) Particle size range.

i) Description of VOC and aldehyde measuring equipment used:

1) Manufacturer, model and serial numbers of instruments, sample collection media and field calibration device;

2) Date, time and results of pre-sampling calibration and post-sampling air flow rate check.

j) Sampling method used for VOC and aldehydes:

1) Sorbents used;

2) Volume sampled and flow rate of pump;

3) Sampling start time and duration.

k) Detection limits of VOC, aldehydes and particulate matter;

l) Printing operating conditions (printing speed, nozzle temperature, layer thickness, filling percentage, and etc.);

m) Printing time (pre-extruding phase, extruding phase, post-extruding phase).

9.2 Data on filament and desktop 3D printer

The following information is to be recorded for test report:

a) Filament family (e.g. ABS, PLA, etc.) and colour;

b) Filament manufacturer and model name;

c) Filament batch;

d) Printer-manufacturer, model name and serial number ;

e) History of the filament and desktop 3D printer (date of production, date of unpacking, storage time in packing, storage time outside of packing, environmental storage conditions before a test, temperature and relative humidity);

f) Type of packaging (for 3D printer and filament — e.g. double layer corrugated cardboard and styrofoam, plastic bag, etc.);

g) External dimensions of desktop MEX-TRB/P machine (maximum length, width and height);

h) Information of the filament containing any additives that are not obvious from the commercial name (carbon fibers, carbon nanotubes, metal, etc.);

i) Test conditions selected from those recommended by the manufacturer:

1) Nozzle temperature tested (including temperature range given from manufacturer and recommended print temperature);

2) Printing speed;

3) Layer thickness;

4) Printing time;

5) Filling percentage (density);

6) Others.

9.3 Description on standard test specimen

The following information is to be recorded for test report:

a) Record the details of standard test specimen;

b) Photo of the printed test specimen.

9.4 Information about test laboratory

The following information is to be recorded for test report:

a) Name and full address of test laboratories (particle emission test, VOCs and aldehyde analysis);

b) Name of the responsible persons (those singing the chain of custody forms at the laboratories).

9.5 Results

The following information is to be recorded for test report:

a) Average particle emission rate per hour, $PER_{h,}$ in h^{-1};

b) Mass of the final test specimen including supports, in g;

c) Total number concentration of fine and ultrafine particles emitted during the operation of a desktop MEX-TRB/P machine, in cm^{-3} and the supporting date [$C_P(t_{start})$, $C_P(t_{stop})$, $C_P(t_1)$, $C_P(t_2)$, t_{start}, t_{stop}, t_1, t_2, etc.];

d) Diagram of particle number concentration similar to Figure 3;

e) Particle loss rate coefficient (β);

f) Particle and chemical emission yield of material melted used in final test specimen, in $\mu g \cdot g^{-1}$;

g) Chemical emission rate : total VOCs and aldehyde, in $\mu g \cdot h^{-1}$;

h) Analysed VOC and aldehyde masses during the extruding phase, in µg;

i) Volume of air sample of VOC and aldehyde during the extruding phase, in m^3;

j) Times the VOC and aldehyde samples were taken during the extruding phase, in h.

Annex A
(normative)

Standard operating condition of a desktop 3D printer

A.1 Purpose

Particle and VOC emission rates during 3D printing process can vary depending on the operating conditions (See Annex C). The procedure outlined in this document is intended to standardize the operating conditions by defining how to set up the printing conditions. If the print conditions are arbitrarily chosen without any rules, particle and VOC emission rates would result in a test result favourable to the manufacturer.

This document is intended to evaluate particle and chemical emission rates not only from the filament itself but also the emissions from the material and desktop MEX-TRB/P machine as one test subject using a filament feedstock during the 3D printing operation.

A.2 Standard operating condition

Table A.1 — Standard operating condition

Item	Standard operating condition
Nozzle temperature	Set the highest temperature among those appropriate nozzle temperature conditions according to material selection by each manufacturer.
Printing speed	Set the printing speed to 50 mm/s. In case the maximum speed is lower than 50 mm/s, set up the maximum speed recommended by the manufacturer.
Layer thickness	Set the highest layer thickness among those provided by manufacturer.
Size of test specimen	Adjust the size of the test specimen for a printing time of at least 4 h after setting up all operating conditions.
Filling percentage(Density)	Set up a filling percentage of the product to 10 %.
Infill pattern	Set the infill pattern which has the lowest density among the providing patterns.
Others	Set a specific default value on other items based on the operating conditions for each desktop 3D printer recommended by manufacturer.

Annex C shows that particle emissions would be significantly different depending on both nozzle temperature and layer thickness compared to the other items of the standard operation condition (Table A.1). Therefore, a tester should select the highest condition of the nozzle temperature and layer thickness within the range given by the manufacturer. However, other items that can apply to the desktop MEX-TRB/P machine in common shall be set up to a specific default value to equalize test conditions for all desktop MEX-TRB/P machines.

Annex B
(normative)

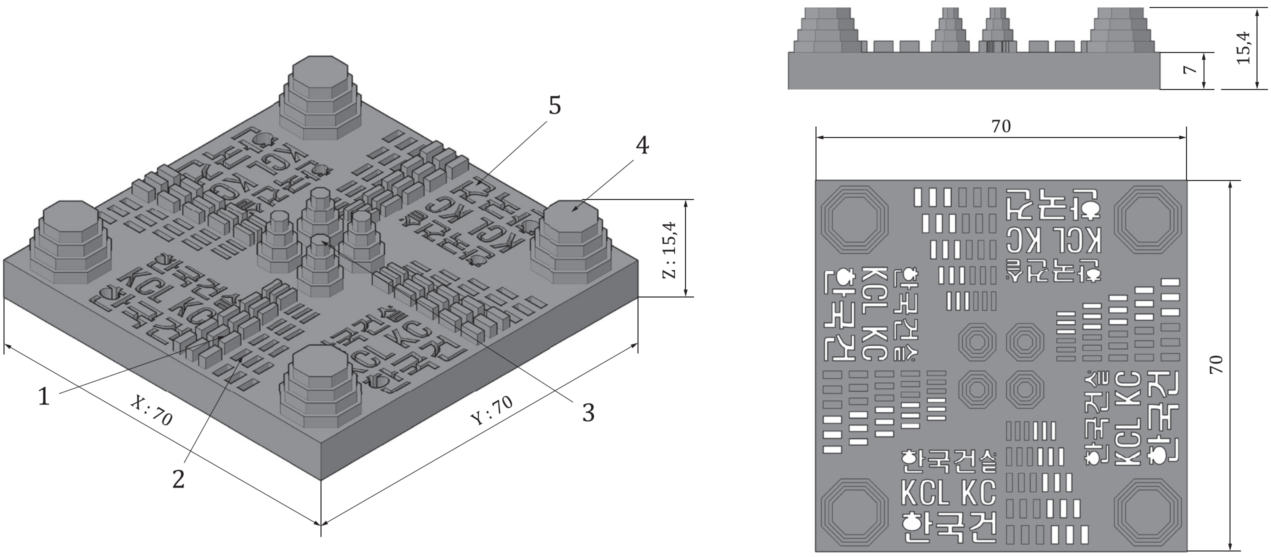
Test specimen

This basic geometry is intended not to test the printing accuracy of the following test specimen, but to test particle and chemical emission rates while extruding this three-dimensional test specimen. The test specimen is comprised of 5 different geometric shapes and made up of STL file format. All dimensions of the structure below are in millimetres. This file format can be downloaded at the link below:

— ISO Online browsing platform: available at https://standards.iso.org/iso/27548/ed-1/en/

B.1 Overall form

Dimensions in millimetres



Key

1 positive rectangular features (B.2)

2 negative rectangular features (B.3)

3 regular octangular tower in the center (B.4)

4 regular octangular tower near the edge (B.5)

5 font types (B.6)

Figure B.1 — Design of the proposed test specimen

A test specimen is comprised of 5 different geometric shapes, where geometry (1), (3), and (4) are on the positive features from the surface, and geometry (2) and (5) are on the negative features. The printer shape is set for LWH : 70 mm, 70 mm, 15,4 mm.

B.2 Positive rectangular features

Dimensions in millimetres

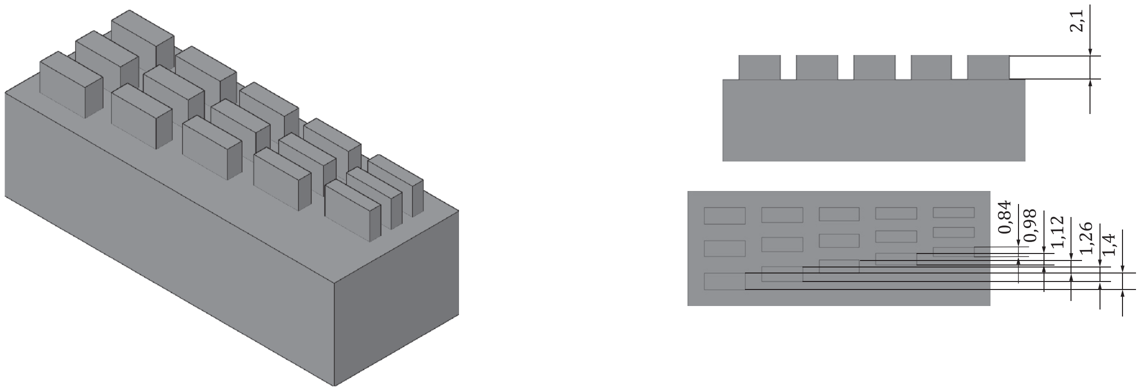


Figure B.2 — Details of the positive rectangular features among 5 shapes shown in Figure B.1

Figure B.2 depicts the geometry (1) of the positive features among 5 shapes shown in Figure B.1. The entire feature is 1,40 mm × 3,50 mm × 2,10 mm. The width of the positive features with the same length and height decreases from 1,40 mm to 1,26 mm, 1,12 mm, 0,98 mm and 0,84 mm.

B.3 Negative rectangular features

Dimensions in millimetres

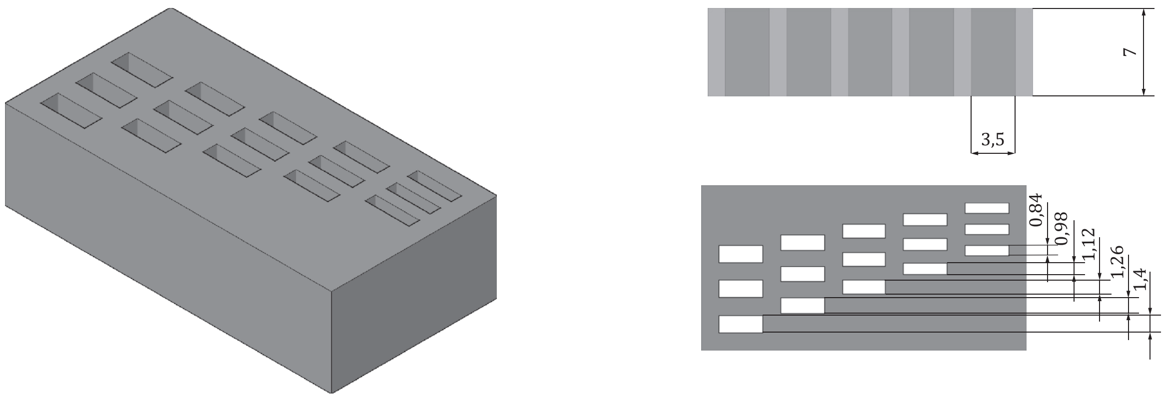


Figure B.3 — Details of the negative rectangular features among 5 shapes shown in Figure B.1

Figure B.3 depicts the geometry (2) of the negative features among 5 shapes shown in Figure B.1. The entire feature is 1,40 mm × 3,50 mm × 7,00 mm. The width of the negative features with the same length and height decreases from 1,40 mm to 1,26 mm, 1,12 mm, 0,98 mm and 0,84 mm.

B.4 Regular octangular tower in the centre

Dimensions in millimetres

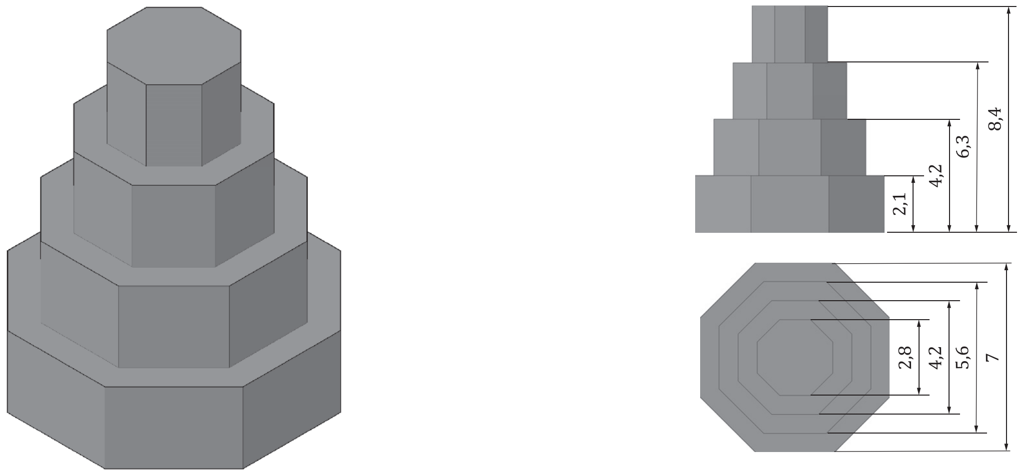


Figure B.4 — Details of the regular octangular tower in the center among 5 shapes shown in Figure B.1

Figure B.4 depicts the geometry (3) of the regular octangular tower in the center among 5 shapes shown in Figure B.1. The bottom feature is 7,00 mm × 7,00 mm × 2,10 mm. The width of the octangular features decreases from 7,00 mm to 5,60 mm, 4,20 mm and 2,80 mm and the height increases from 2,10 mm to 4,20 m, 6,30 mm and 8,40 mm.

B.5 Regular octangular tower near the edge

Dimensions in millimetres

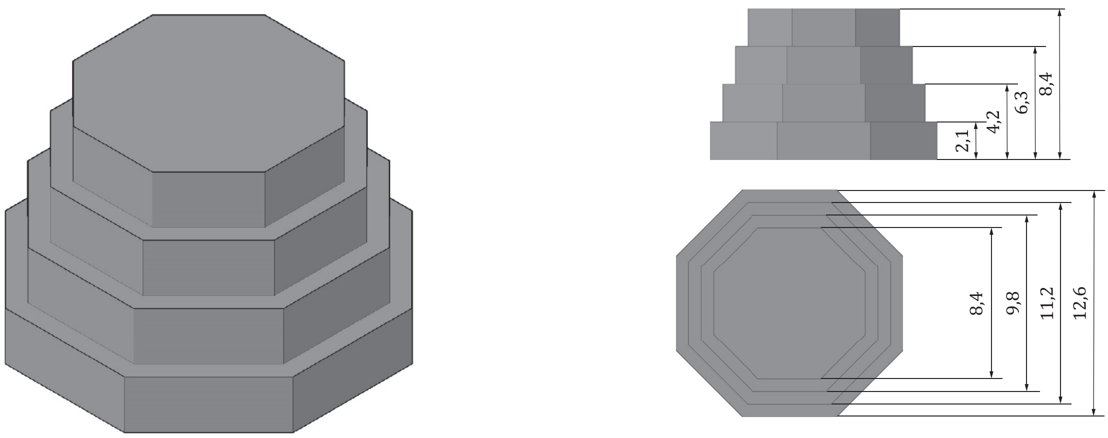


Figure B.5 — Details of the regular octangular tower near the edge among 5 shapes shown in Figure B.1

Figure B.5 depicts the geometry (4) of the regular octangular tower near the edge among 5 shapes shown in Figure B.1. The bottom feature is 12,60 mm × 12,60 mm × 2,10 mm. The width of the octangular features decreases from 12,60 mm to 11,20 mm, 9,80 mm and 8,40 mm and the height increases from 2,10 mm to 4,20 mm, 6,30 mm and 8,40 mm.

B.6 Font types

Dimensions in millimetres

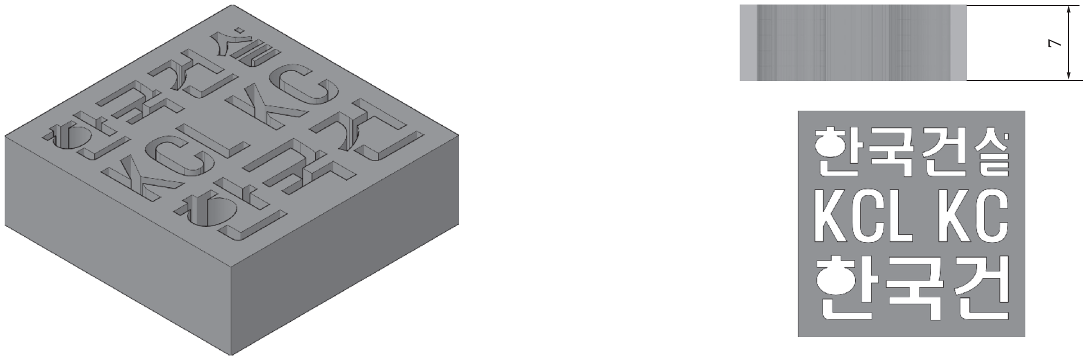


Figure B.6 — Details of the font types among 5 shapes shown in Figure B.1

Figure B.6 depicts the geometry (5) of the font types among 5 shapes shown in Figure B.1. The entire geometry is on the negative features. The font types are comprised of different languages in various shapes and sizes.

Annex C
(informative)

Examples of the particle and chemical emission rates

C.1 Example of the particle emission rates, PER(*t*), according to the test operating conditions

The results below are measured using the same filament (ABS) and desktop MEX-TRB/P machine in the 5 m^3 test chamber in order to check how the results are changeable depending on the test operating conditions.

When the test operating conditions are set up in the same conditions except for model size or shape (See Table C.1) and printing speed (See Table C.3), the relative percentage difference (RPD) is not significant. It means that the model size or shape, and printing speed do not affect particle emission rates.

While the test operating conditions are set up in the same condition except for nozzle temperature (See Table C.2) and layer thickness (See Table C.4), the RPD values between nozzle temperature and layer thickness are remarkably different. It means that the particle emission rates can be changeable depending on the nozzle temperature and layer thickness.

Therefore, the measurement of a desktop MEX-TRB/P machine should be carried out according to the standard operating conditions (See Table A.1).

Table C.1 — Example of PER(*t*) according to the shape and size of printing model

Printing model	**No.**	**Nozzle temperature** °C	**Printing speed** mm·s^{-1}	**Layer thickness** mm	**PER(*t*)** Particles·h^{-1}	**RSD** %	**RPD** %
Model 1	1	250	25	0,2	$2,3 \times 10^{12}$	14,1	20,6
	2				$2,6 \times 10^{12}$		
($L \times W \times H$: 35 mm × 35 mm × 56 mm)	3				$1,9 \times 10^{12}$		
Model 2	1	250	25	0,2	$2,0 \times 10^{12}$	9,8	
	2				$1,8 \times 10^{12}$		
($L \times W \times H$: 57 mm × 57 mm × 20 mm)	3				$1,7 \times 10^{12}$		

Table C.2 — Example of PER(t) according to the nozzle temperature

Printing model	No.	Nozzle temperature °C	Printing speed $mm \cdot s^{-1}$	Layer thickness mm	PER(t) $Particles \cdot h^{-1}$	RSD %	RPD %
Model 2 	1	250	25	0,2	$2,0 \times 10^{12}$	9,8	144
	2				$1,8 \times 10^{12}$		
	3				$1,7 \times 10^{12}$		
($L \times W \times H$: 57 mm × 57 mm × 20 mm)	1	230	25	0,2	$2,9 \times 10^{11}$	4,4	
	2				$3,1 \times 10^{11}$		
	3				$3,1 \times 10^{11}$		

Table C.3 — Example of *PER(t)* according to the printing speed

Printing model	No.	Nozzle temperature °C	Printing speed $mm \cdot s^{-1}$	Layer thickness mm	PER(t) $Particles \cdot h^{-1}$	RSD %	RPD %
Model 2 	1	250	25	0,2	$2,0 \times 10^{12}$	9,8	12
	2				$1,8 \times 10^{12}$		
	3				$1,7 \times 10^{12}$		
($L \times W \times H$: 57 mm × 57 mm × 20 mm)	1	250	35	0,2	$1,8 \times 10^{12}$	11,9	
	2				$2,1 \times 10^{12}$		
	3				$2,3 \times 10^{12}$		

Table C.4 — Example of PER(t) according to the layer thickness

Printing model	No.	Nozzle temperature °C	Printing speed $mm \cdot s^{-1}$	Layer thickness mm	PER(t) $Particles \cdot h^{-1}$	RSD %	RPD %
Model 2 	1	250	25	0,2	$2,0 \times 10^{12}$	9,8	52,4
	2				$1,8 \times 10^{12}$		
	3				$1,7 \times 10^{12}$		
($L \times W \times H$: 57 mm × 57 mm × 20 mm)	1	250	25	0,1	$1,3 \times 10^{12}$	11,9	
	2				$1,1 \times 10^{12}$		
	3				$1,1 \times 10^{12}$		

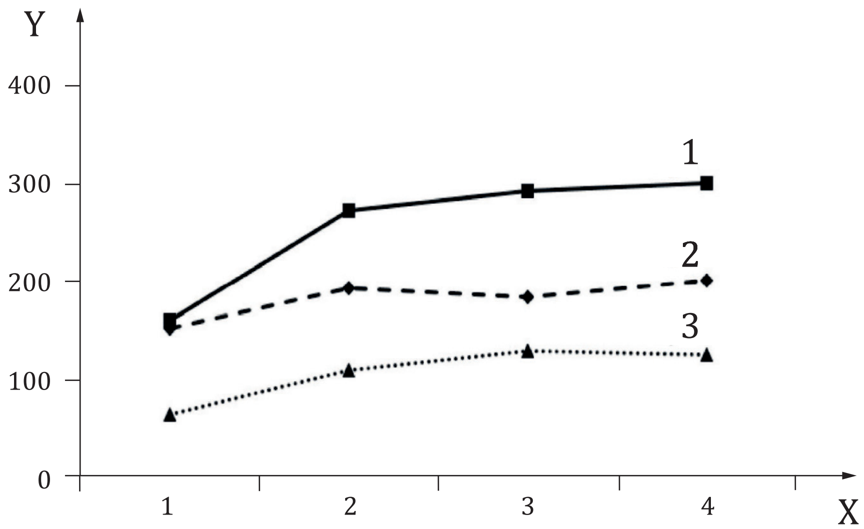
C.2 Example of the chemical concentration per each hour

The results below are measured to investigate how the TVOC concentrations are changeable depending on the kind of the desktop MEX-TRB/P 3D printer and its materials. The test results (Table C.5) show that chemical concentrations would be various depending on the kinds of the desktop MEX-TRB/P 3D printer and material. When TVOC concentrations from the desktop MEX-TRB/P 3D printer during operation are sampled each hour, each concentration over time is increasing, reaching steady-state after 3 h (See Figure C.1).

Therefore, the total printing time for measuring the emission rates should be continued for at least 4 h.

Table C.5 — Test results

Item	Unit	Brand-material	1 h	2 h	3 h	4 h	Mean
TVOC	μg/m^3	A-ABS	152,4	194,4	184,4	202,0	183,3
		B-ABS	161,3	273,5	293,6	301,1	257,4
		C-PLA	65,3	109,9	130,5	127,0	108,2



Key

X time (hours)

Y concentration (μg /m^3)

1 A-brand - ABS filament

2 B-brand - ABS filament

3 C-brand - PLA filament

Figure C.1 — TVOCs concentration emitted from ETC over time

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