Assessment of the air purifier effectiveness under model conditions

A Staszowska
Lublin University of Technology, Faculty of Environmental Engineering, Nadbystrzycka 40, Lublin, Poland
a.staszowska@pollub.pl

Abstract. The aim of this study was to evaluate the operation of a stationary air purifier under the model conditions of a non-occupied test chamber with dimensions similar to a typical living room. The purifier was equipped with a system for neutralization of volatile organic compounds, disinfection (neutralizing chamber with a system of UVA lamps, plates made of TiO₂, UVC lamp settings) and HEPA filters at the air outlet of the device. The conducted research focused on the effectiveness of removing bacterial bioaerosols (M. luteus and B. subtilis) as well as formaldehyde and the sum of volatile organic compounds. The assessment was made for two ranges of fan flow, 100 and 300 m³/h (Standard and Turbo). The unit shows high efficiency in removing the tested bacterial strains, i.e. 100% after 60 and 90 minutes, respectively. Higher efficiency occurred for lower fan output. However, its effectiveness in removing TVOCs did not exceed 58%. Additionally, the formation of formaldehyde was noted during the operation of the purifier.

1. Introduction
Air quality is currently the basic factor determining the health of a modern society. In many countries, there is a state of high air pollution, which is caused by the uncontrolled combustion of conventional fuels and transport [1]. Particle pollutants (PM 10, PM 2.5, PM 0.1) and chemical compounds present in the air have a negative impact on the human health, increasing sickness absenteeism at work and, in the case of children, reduce their ability to learn [2-6]. The results of epidemiological studies confirm the increased cancer incidence in the areas with high air pollution. There is also evidence that a higher incidence of respiratory, cardiovascular and nervous system diseases is associated with an increased mortality among the people permanently exposed to breathing polluted air [7]. We spend almost 90% of our lives indoors, where we are also exposed to biological and chemical pollutants [8-9]. While the main source of PM in the indoor air is the infiltration of the outdoor air, the primary source of fungal and bacterial bioaerosols are the users themselves [10,11]. The group of volatile organic compounds is considered among the chemical substances that pose the greatest health risk. Many of them have proven carcinogenic and mutagenic properties. The source of VOCs is the emission from building and finishing materials as well as household appliances [12,13]. Social awareness of the threats posed by breathing polluted air is constantly increasing and forces us to search for effective solutions to this problem [14]. The improvement of air quality can be achieved by using air purifiers. These are usually portable devices equipped with systems for dust extraction, VOC neutralization and air disinfection [15,16]. While the market of air purifiers on a global scale is growing every year, there is still a lack of scientific data on how the offered purifier units perform under model and real conditions. The
available literature data focuses only on the tests of the purifier prototypes that are carried out in test chambers with a small cubic volume (1-2 m$^3$), which does not reflect the actual dimensions and conditions in residential or office premises. It should also be remembered that most of the stationary indoor air purification units sold in the world do not have scientifically proven effectiveness in the removal of bioaerosol, volatile organic compounds or suspended dust. In advertising leaflets, producers and distributors of purifiers often provide the value of the effectiveness of removing a given group of pollutants at the level of up to 99.99%, which is a pure advertising procedure. Therefore, there is a need to conduct research that will enable to objectively evaluate the operation of these devices. Hence, the aim of this survey was to evaluate the efficiency of operation of a portable air purifier unit under model conditions. The bioaerosol concentration, formaldehyde (HCOH) and sum of volatile organic compounds (TVOCs) were measured in real time. The temperature and relative humidity were also monitored during this study.

2. Materials and Methods

The tests conducted under model conditions concerned the measurement of the following parameters:
- microbiological: concentration of *M. luteus* and *B. subtilis*;
- chemical: concentration of formaldehyde (HCOH), concentration of total volatile organic compounds (TVOCs).

The microbiological measurements were performed in the Standard (100 m$^3$/h) and Turbo (300 m$^3$/h) operating settings. The concentrations of HCOH and TVOCs were measured only in the Standard setting. The tests were carried out in accordance with its own methodology developed in the Laboratory of Indoor and Outdoor Air Quality (Department of Indoor and Outdoor Air Quality, Faculty of Environmental Engineering, Lublin University of Technology) – Assessment of the effectiveness of portable air purifier units.

2.1. Air purifier

The object of the research was a portable air purifier with a neutralization chamber created by a photocatalytic system (UVA lamps and TiO$_2$ coated plates) and a set of UVC lamps. There is a pre-filter at the inlet of the purifier and a HEPA filter at the air outlet of the device. The air inlet to the purifier is located at the bottom of the device and the outlet at the top. The manufacturer offers the possibility of controlling the fan’s work flow in 4 ranges. The tested device was brand new. The device dimensions were as follows: 1273x684x334 mm (height/width/depth), weight 72 kg. The device is recommended for rooms up to 500 m$^2$. Unfortunately, the purifier manufacturer does not provide the construction details (dimensions and operating parameters) of the components of the tested device (filters, photocatalysis chamber equipment).

2.2. Test chamber

The model tests were carried out in a research chamber with dimensions of 4x4x3 m/m/ m (height/width/depth); walls made of stainless steel; airtight room; no windows; temperature setting option; for the tests with an air purifier, the recommended temperature is 22-25°C; relative air humidity at the range 50 – 55%. The test chamber meets the requirements of ISO 16000-36: 2018 (E). Indoor air. Standard method for assessing the reduction rate of culturable airborne bacteria by air purifiers using a test chamber. The air purifier was placed in the center of the chamber, opposite the entrance. A test bioaerosol nebulizer and a fan were set up at a distance of 0.5 m from the inlet to the purifier. Single-stage impactors were placed at the air inlet and outlet of the purifier unit. An additional third impactor was placed behind the purifier, for the control purposes. The measuring points for internal temperature and relative air humidity were located in three points of the chamber, at the height of the air inlet to the purifier.
2.3. Microbiological measurements

The time of air sampling was 5 minutes. The culture media for bacteria was TSA medium (Tryptone Soya Agar), BTL Spółka z o.o., Poland. The incubation conditions were as follows: Micrococcus luteus: PCM 525 temperature 37°C, reading after 24h/48h; Bacillus subtilis PCM 2021 temperature 37°C, reading after 24h/48h. After incubation, the colonies grown on the plates were counted using a standard colony counter, taking into account the correction tables provided by the impactor manufacturer and converted into m³ of tested air. In the studies, a suspension of the test strain was prepared in McFarland scale and a series of ten-fold dilutions were made to obtain the appropriate concentration of the suspension. The suspension of the specified starting concentration was introduced into the test chamber using an aerosol generator. The nebulization time in the test chamber was 60 minutes. The air from the measuring points was collected by means of single-stage impactors. The air at the inlet to the purifier was used as the background.

The following dilutions were tested: for Micrococcus luteus – 1.6*10⁴ CFU/ml and 6.2*10⁴ CFU/ml; for Bacillus subtilis – 1.3*10⁵ CFU/ml and 1.6*10⁵ CFU/ml.

Before starting work with the purifier, the surface of its casing was disinfected with 96% ethanol (POCH, Poland), i.e. prior to nebulization and strain change. The room of the test chamber was disinfected each time before starting the measurements with a stationary germicidal lamp. Then, the air purity in the chamber was measured – the number of colonies grown on the plates ranged from 0 to 1. Additionally, the cleanliness of the surface was controlled by swabbing.

2.4. Chemical measurements

The measurements of HCHO, TVOCs were performed at 5 measuring points at a height of 1 m and a distance from the purifier unit of 0.5 m. The arithmetic mean of the above-mentioned measurements was used to calculate the removal efficiencies. Under the model conditions, i.e. in the test chamber, HCOH and TVOC concentrations were measured in the following configurations: no additional source of VOCs; TVOCs> 0 ppm; isopropanol (for HPLC, POCH Poland) as an additional source of VOCs (Standard setting). The starting point of measurements was the HCOH concentration of 0.00 ppm. The following set of measuring devices was used to carry out the tests: formaldehyde and total volatile organic compounds TVOC meters: VFM200 Extech, Instruments; SKC Biostage, US single-stage impactors; test bioaerosol generator ATM 226 TOPAS GmbH, Germany; LB-520 LAB-EL thermohygrometers, Poland. The device was tested in series lasting 210 minutes.

3. Results

Both strains used in the research are gram positive bacteria, which show greater resistance to UVC radiation than the gram-negative bacteria. Both M. luteus and B. subtilis are common components of indoor air bioaerosol in residential and public buildings. In the case of the M. luteus strain (Tables 1), after 30 minutes of operation, the disinfection efficiency was over 90%, and 100% was achieved after 90 minutes. During both tests 1 and 2, no bacteria were found at the air outlet of the purifier. In the case of the second strain of B. subtilis, the disinfection efficiency was similar for the Standard setting.

In the 30th minute of purifier operation, the initial concentration of bacteria decreased by an average of 95.9%; 100% efficiency was achieved 90 minutes after turning on the device. In the case of the Turbo option, after 30 minutes of operation, an 89.9% reduction of the tested strain was demonstrated. The purifier with disinfection on the Turbo option was much worse. Complete removal of the test strain was recorded only 120 minutes after switching on and uninterrupted operation of the purifier. As for the test with the first strain, no bacteria were detected in the air at the outlet of the purifier. The obtained results indicate a faster reduction of the tested bacterial strains. The obtained results indicate a faster reduction of the tested bacterial strains for the Standard option. This can be explained by the longer time of contact of bacteria with the disinfectant, which in this case is probably the radiation produced by a set of UVC lamps. Due to the parallel operation of UVA and UVC lamps, it is not possible to indicate the share of photocatalysis in the air disinfection process.
### Table 1. Micrococcus luteus removal efficiency [CFU/m³].

| Sampling point | Time of operation [min] | 0 | 30 | 60 | 90 | 120 | 150 | 180 | 210 |
|---------------|-------------------------|---|----|----|----|-----|-----|-----|-----|
| **STANDARD**  |                         |   |    |    |    |     |     |     |     |
| inlet [CFU/m³] – test 1 | 1083 | 67 | 17 | 0  | 0  | 0   | 0   | 0   | 0   |
| inlet [CFU/m³] – test 2 | 1608 | 108 | 0  | 0  | 0  | 0   | 0   | 0   | 0   |
| outlet [CFU/m³] – test 1 | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   |
| outlet [CFU/m³] – test 2 | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   |
| removal [%] – test 1 | 0  | 93.8 | 98.4 | 100 | -  | -   | -   | -   | -   |
| removal [%] – test 2 | 0  | 93.3 | 100 | -  | -   | -   | -   | -   | -   |
| removal [%] average | 0  | 93.6 | 99.2 | 100 | -  | -   | -   | -   | -   |
| **TURBO**     |                         |   |    |    |    |     |     |     |     |
| inlet [CFU/m³] – test 1 | 829  | 117 | 92 | 8  | 0  | 0   | 0   | 0   | 0   |
| inlet [CFU/m³] – test 2 | 1275 | 233 | 125 | 8  | 0  | 0   | 0   | 0   | 0   |
| outlet [CFU/m³] – test 1 | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   |
| outlet [CFU/m³] – test 2 | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   |
| removal [%] – test 1 | 0  | 85.9 | 88.9 | 99.0 | 100 | -   | -   | -   | -   |
| removal [%] – test 2 | 0  | 81.7 | 90.0 | 99.4 | 100 | -   | -   | -   | -   |
| removal [%] average | 0  | 83.8 | 89.5 | 99.2 | 100 | -   | -   | -   | -   |

### Table 2. Bacillus subtilis removal efficiency [CFU/m³].

| Sampling point | Time of operation [min] | 0 | 30 | 60 | 90 | 120 | 150 | 180 | 210 |
|---------------|-------------------------|---|----|----|----|-----|-----|-----|-----|
| **STANDARD**  |                         |   |    |    |    |     |     |     |     |
| inlet [CFU/m³] – test 1 | 1325 | 83 | 42 | 0  | 0  | 0   | 0   | 0   | 0   |
| inlet [CFU/m³] – test 2 | 1175 | 22 | 8  | 0  | 0  | 0   | 0   | 0   | 0   |
| outlet [CFU/m³] – test 1 | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   |
| outlet [CFU/m³] – test 2 | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   |
| removal [%] – test 1 | 0  | 93.7 | 96.8 | 100 | -  | -   | -   | -   | -   |
| removal [%] – test 2 | 0  | 98.1 | 99.3 | 100 | -  | -   | -   | -   | -   |
| removal [%] average | 0  | 95.9 | 98.1 | 100 | -  | -   | -   | -   | -   |
| **TURBO**     |                         |   |    |    |    |     |     |     |     |
| inlet [CFU/m³] – test 1 | 1775 | 125 | 71 | 40 | 0  | 0   | 0   | 0   | 0   |
| inlet [CFU/m³] – test 2 | 1050 | 140 | 100 | 26 | 0  | 0   | 0   | 0   | 0   |
| outlet [CFU/m³] – test 1 | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   |
| outlet [CFU/m³] – test 2 | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   |
| removal [%] – test 1 | 0  | 93.0 | 96.0 | 97.7 | 100 | -   | -   | -   | -   |
| removal [%] – test 2 | 0  | 86.7 | 90.5 | 97.5 | 100 | -   | -   | -   | -   |
| removal [%] average | 0  | 89.9 | 93.3 | 97.6 | 100 | -   | -   | -   | -   |
The second goal of the research was to determine the efficiency of the purifier in the removal of formaldehyde and volatile organic compounds (Tables 3 to 6).

Table 3. Formaldehyde concentration in test chamber – without additional VOC source [ppb], Standard.

| Time of operation | 1   | 2   | 3   | 4   | 5   | average | Removal [%] |
|-------------------|-----|-----|-----|-----|-----|---------|-------------|
| 0 min             | 0   | 0   | 0   | 0   | 0   | 0       | -           |
| 30 min            | 0   | 0   | 0   | 0   | 0   | 0       | -           |
| 60 min            | 30  | 30  | 30  | 20  | 30  | 28      | -           |
| 90 min            | 30  | 40  | 30  | 30  | 30  | 32      | -           |
| 120 min           | 30  | 30  | 40  | 40  | 50  | 38      | -           |
| 150 min           | 20  | 30  | 50  | 50  | 50  | 40      | -           |
| 180 min           | 30  | 40  | 40  | 40  | 50  | 40      | -           |
| 210 min           | 40  | 20  | 30  | 20  | 30  | 28      | -           |

Table 4. Formaldehyde concentration in test chamber – with isopropanol as VOCs source [ppb], Standard.

| Time of operation | 1   | 2   | 3   | 4   | 5   | average | Removal [%] |
|-------------------|-----|-----|-----|-----|-----|---------|-------------|
| 0 min             | 0   | 0   | 0   | 0   | 0   | 0       | -           |
| 30 min            | 0   | 0   | 0   | 0   | 0   | 0       | -           |
| 60 min            | 0   | 0   | 0   | 0   | 0   | 0       | -           |
| 90 min            | 50  | 70  | 60  | 50  | 50  | 56      | -           |
| 120 min           | 50  | 60  | 50  | 50  | 50  | 52      | -           |
| 150 min           | 50  | 50  | 60  | 50  | 60  | 54      | -           |
| 180 min           | 70  | 60  | 50  | 70  | 70  | 64      | -           |
| 210 min           | 60  | 70  | 60  | 60  | 60  | 62      | -           |
| 360 min           | 60  | 50  | 60  | 50  | 50  | 54      | -           |

Table 5. TVOC concentrations in test chamber without additional VOCs source [ppb], Standard.

| Time of operation | 1    | 2    | 3    | 4    | 5    | average | Removal [%] |
|-------------------|------|------|------|------|------|---------|-------------|
| 0 min             | 1120 | 1100 | 1140 | 1120 | 1120 | 1052    | 0           |
| 30 min            | 980  | 990  | 980  | 980  | 990  | 867     | 5.9         |
| 60 min            | 750  | 760  | 750  | 740  | 750  | 750     | 40.9        |
| 90 min            | 740  | 750  | 750  | 760  | 750  | 732     | 40.9        |
| 120 min           | 710  | 720  | 710  | 710  | 720  | 707     | 43.3        |
| 150 min           | 700  | 690  | 710  | 700  | 700  | 693     | 44.9        |
| 180 min           | 700  | 680  | 690  | 680  | 680  | 696     | 46.5        |
| 210 min           | 520  | 510  | 500  | 500  | 540  | 514     | 57.5        |
Table 6. TVOC concentrations in test chamber with isopropanol as VOCs source [ppb]. Standard.

| Time of operation | Sample | average | Removal [%] |
|-------------------|--------|---------|-------------|
| 0 min             | 1      | 3950    | 3595        | 0           |
|                   | 2      | 3960    |             |             |
|                   | 3      | 3950    |             |             |
|                   | 4      | 4000    |             |             |
|                   | 5      | 4000    |             |             |
| 30 min            | 1      | 3240    | 3134        | 19.0        |
|                   | 2      | 3200    |             |             |
|                   | 3      | 3200    |             |             |
|                   | 4      | 3250    |             |             |
|                   | 5      | 3200    |             |             |
| 60 min            | 1      | 3000    | 2923        | 21.5        |
|                   | 2      | 3050    |             |             |
|                   | 3      | 3050    |             |             |
|                   | 4      | 3100    |             |             |
|                   | 5      | 3050    |             |             |
| 90 min            | 1      | 2840    | 2623        | 30.6        |
|                   | 2      | 2800    |             |             |
|                   | 3      | 2800    |             |             |
|                   | 4      | 2740    |             |             |
|                   | 5      |         |             |             |
| 120 min           | 1      | 2500    | 2410        | 39.0        |
|                   | 2      | 2400    |             |             |
|                   | 3      | 2400    |             |             |
|                   | 4      | 2410    |             |             |
|                   | 5      | 2490    |             |             |
| 150 min           | 1      | 2170    | 2142        | 43.5        |
|                   | 2      | 2170    |             |             |
|                   | 3      | 2170    |             |             |
|                   | 4      | 2170    |             |             |
|                   | 5      | 2240    |             |             |
| 180 min           | 1      | 1950    | 2004        | 48.1        |
|                   | 2      | 1950    |             |             |
|                   | 3      | 1950    |             |             |
|                   | 4      | 2050    |             |             |
|                   | 5      | 2050    |             |             |
| 210 min           | 1      | 1950    | 2004        | 49.4        |
|                   | 2      | 1950    |             |             |
|                   | 3      | 1950    |             |             |
|                   | 4      | 1950    |             |             |
|                   | 5      | 2000    |             |             |

In the case of formaldehyde, which is a recognized carcinogen, the results show that the purifier itself is the source of this compound. Moreover, the operation of the device does not indicate any effectiveness in its removal. The measured formaldehyde concentrations significantly exceed the values recognized as safe in the indoor environment. This may be due to the photocatalytic oxidation process itself. The manufacturer, as he declares himself, has placed UVA and UVC lamps in one neutralization chamber. It favors the formation of by-products from the photocatalysis of other volatile organic compounds [17,18]. Therefore, the degradation process can be considered incomplete and in the case of prolonged use of this device, it may adversely affect the health of the room users [19-21].

The obtained results indicate that in the case of the tested purifier, the use of photocatalysis is not favorable. Perhaps better efficiency in the operation of the device could be achieved by using ordinary carbon filters instead of the photocatalytic oxidation process.

4. Conclusions
   • Faster reduction of bacterial bioaerosol occurred with the Standard setting which corresponds to lower fan efficiency and therefore a longer contact time of air with the disinfecting system.
   • No strains of the tested bacteria were found in the outlet air in the chamber studies.
   • The measured values obtained for formaldehyde and the sum of volatile organic compounds are inconclusive. Hence, it is not possible to assess the efficiency of the purifier operation in this respect.

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