Evaluation of sensor-based air cleaners to remove $PM_{2.5}$ and TVOC from indoors with pollutant sources of smoking and burning candles

Kathrine Andersen[1], Stig Koust[2], Freja Rydahl Rasmussen[2], and Li Rong[*1]

1 Department of Civil and Architectural Engineering
Inge Lehmanns Gade 10, 8000 Aarhus
Denmark
**Corresponding author: li.rong@cae.au.dk*

2 Danish Technological Institute
Kongsvang Alle 29, 8000 Aarhus C
Denmark

ABSTRACT

Indoor air quality in residential buildings has been attracting more attention from the public. Many portable air cleaner products have been developed and are available in the market. Manufactures generally claim that those portable air cleaners can efficiently remove $PM_{2.5}$ and/or TVOC and can also remove virus from the indoor air. However, no standards are available to have the claimed efficiency comparable and thus unclear effect in applications at homes. This study tested four air cleaners with embedded sensors by using pollutant sources of smoking and burning candles, which exist widely at homes, in a climate chamber (20 m^3) without turning on the mechanical ventilation system, respectively. The concentrations of $PM_{2.5}$ and TVOC measured by the embedded sensors were compared with the recorded data by instruments with high accuracy such as DustTrak (8533), SMPS (scanning mobility particle sizer, 3910), OPS (optical particle sizer, 3330) and Ion Science Tiger TVOC gas detector. The results showed that the embedded sensors generally underestimated the PM2.5 mass concentration and thus influenced the regulation of fan speeds of air cleaners. Only the embedded sensor of one air cleaner could provide comparable $PM_{2.5}$ mass concentration with the data measured by DustTrak when the concentration was within the detected range of the embedded sensor (< 1000 µg/m^3). The underestimated $PM_{2.5}$ mass concentrations led to the air cleaners to quickly switch to the lowest fan speed although the $PM_{2.5}$ mass concentration was still far too high. The embedded sensors cannot properly detect the mass concentrations of ultrafine particles released from burning candles. The air cleaners do not regulate its fan speeds based on TVOC concentrations measured by the embedded TVOC sensors. The obtained results highlighted the limited accuracy of the embedded low-cost sensors. It is imperative to issue standards to guide manufacturer to properly report the efficiency of their products and to clearly claim the performance of air cleaners.

KEYWORDS

Burning candles, Efficiency, $PM_{2.5}$, Portable sensor-based air cleaner, Smoking

1 INTRODUCTION

Nowadays people spend over 90 % of their time indoors. Ensuring indoor air quality (IAQ) is thus imperative. However, many pollutant sources exist in indoor environments, especially at home where the house owners can conduct any activities they want. Various studies have been conducted to identify the pollutant sources behind daily household activities and which ones had large impact on IAQ. One activity, which has a major influence on the emission of particles, is smoking cigarettes (Suryawanshi et al., 2016). The major pollutants from smoking are particulate matters (PM). $PM_{2.5}$ has a harmful impact on human's health and a long-term exposure to $PM_{2.5}$ negatively affects the lungs (Yang et al., 2021). The concentration of $PM_{2.5}$ can be around 91 % higher in the home of smoker compared to the residence of a non-smoker (Daher et al., 2011, McCormack et al., 2008, Abdel-Salam, 2021). Smoke from tobacco have also been proven to emit VOCs, some of which have been identified to have a negative effect on people's health and can cause illnesses such as allergies and asthma (Wang et al., 2012). Another common indoor activity is burning candles, which is the largest indoor source of ultrafine particles in Denmark (Bek. et al., 2013). Ultrafine particles have also been discovered to have a harmful impact on human's health (Schraufnagel, 2020). During the burning of candles, a large amount of ultrafine particles are emitted while $PM_{2.5}$ concentration is quite low (Hansen et al., 2018). However, when candles are lit, certain VOCs can be emitted as a by-product of the burning (Bari et al., 2015). The extinguishing of candles causes the black carbon concentration to rise, which is a by-product of soot and the largest concentration is emitted when a candle is blown out (Hegde et al., 2020).

Recently, people have become more aware of the importance of IAQ. This increased awareness has amplified the market for air-cleaning technologies. One of the popular products to improve IAQ is portable air cleaners. Besides the main filtration system, many air cleaners have additional cleaning techniques, which have been claimed to speed up the removal rate of pollutants in the air (Luengas et al., 2015). For example, it was acclaimed that virus e.g. COVID-19 and VOCs/TVOCs can also be removed from the air besides $PM_{2.5}$ (Liu et al., 2022, Chen et al., 2005). However, the removal efficiency of $PM_{2.5}$ and VOCs/TVOCs varied significantly. Besides, many test methods and standards used to quantify the portable air cleaner's efficiency are available. One study showed that the obtained efficiencies of air cleaner tested by different methods were often incomparable and could be misleading (Harriman et al., 2019). The air cleaners are also evaluated based on different performance indices, which makes it further difficult to compare results obtained from different air cleaners. Almost every test monitored different size intervals of PMs and used different pollutant sources (Afshari et al., 2022). The typical pollutant source used in those tests was cigarette smoking, road dust or pollen. The performance of the air cleaner was often evaluated based on the amount of time needed for air cleaner to clean the polluted air (Chan and Cheng, 2006). However, none of these studies have focused on pollutant sources, which could emit mostly ultrafine particles such as burning candles.

To control the portable air cleaner, embedded low-cost sensors are implemented to simplify the regulations of air cleaner by consumers (Koust and Rydahl, 2022). The most commonly used type of low-cost sensors are optical sensors, which are based on light scattering(Alfano et al., 2021), but it is not clear if the same principle has been used for those embedded sensors. The circulated ventilation rate is regulated by fan speeds based on the measured concentrations of pollutants e.g. PMs and TVOCs by embedded sensors. The accuracy of sensors and their interaction with fan auto-mode is a concern and hardly studied. The ability to measure $PM_{2.5}$ of two embedded sensors in air cleaners was investigated under two different conditions (He et al., 2020) by using a nano-sliver based surface cleaner as a pollutant source in a test chamber, and in a residential house with the pollutant source of cooking. However, the pollutant source smoking, a standardised tests of air cleaner, was not tested. The fan speed regulation under auto-mode was investigated in another study (Huang et al., 2021). The results showed that the auto-mode could be the most effective in removing particles compared to manual regulation unless a sudden high concentration arose. None of the residents in these apartments were smokers and the concentration of ultrafine particles was not monitored and analysed. The accuracy of the sensors was not investigated either.

The objectives of this study were (1) to investigate the accuracy of the embedded sensors of four selected air cleaner when pollutant sources were smoking and burning candles, respectively; (2) to study the regulation of fan speeds at auto-mode per the measured concentration of $PM_{2.5}$ and/or TVOC of the four selected air cleaner.

2 METHODOLOGY

Four air cleaner with embedded sensors to measure concentrations of $PM_{2.5}$/TVOC were tested with pollutant sources of smoking and burning candles in a climate chamber (20 m^3) without turning mechanical ventilation system on. The surfaces of the chamber were covered by inert FEP to ensure that none of the particles could attach to the chamber wall surfaces.

The concentrations of $PM_{2.5}$ and TVOC measured by the embedded sensors were compared with the recorded data by advanced instruments. The DustTrak (8533) measures the mass concentration of particles with size ranging between 0.1 µm to 2.5 µm, logs the data with a sampling frequency of 60 s and a time constant of 1 s. The SMPS (scanning mobility particle sizer, 3910) connected to a UCPC (Ultrafine Condensation Particle Counter, 3776) was used to measure the total number of ultrafine particles. The measured size was between 6.04 nm and up till 220.7 nm. To monitor the TVOC concentration, the Tiger (Ion Science Tiger TVOC gas detector) was employed. To ascertain similar test conditions in all measurements, the C.A 1510 was used to monitor the temperature and relative humidity in the chamber.

2.1 The selected four air cleaners

Four air cleaners were selected by using the criteria that it is possible to register the concentration of $PM_{2.5}$ from the embedded sensors and to control the air cleaner from outside of the test chamber. Air cleaner selected in this study have been anonymised and assigned a number from 1 to 4. More information can be found in Table 1. The pre-filter is used to catch the coarse particles and activated carbon is used to remove both particles and TVOCs. The lowest level of fan speed of air cleaner 3 is only used for fan start. The sensor of air cleaner 3 can measure concentrations of PM_1 and PM_{10} besides $PM_{2.5}$. Although the TVOC concentration was measured for air cleaner 4, no data could be extracted.

Table 1 Summary of four selected air cleaner

Air cleaner	1	2	3	4
Filters/cleaning technology	Pre-filter/EPA 12 combination filter/UV-C light	Pre-filter/HEPA filter/activated carbon filter	Pre-filter/EPA 12 filter/E12 filter/ionizer	Fiber mesh pre-filter/activated carbon/UV-C light
Fan speed level	4	3	5	4
TVOC sensor?	No	No	Yes	Yes*
Placement of sensors	N/A	At the back	On the top	Center of lateral side
Type of sensors	N/A	N/A	N/A	N/A

* No data can be extracted from air cleaner 4.

2.2 The experimental design

Two types of experiments were conducted and referred as type 1 and type 2, respectively. The type 1 smoking tests were conducted based on the standard ANSI/AHAM AC-1, while the type 2 smoking tests were a modified version of this standard, which was introduced later. The placement of air cleaner, pollutant source, standing fan and sampling points is shown in Figure 1. The same set-ups were followed for all measurements, namely: (1) placing the air cleaner in the centre of the test chamber, around 1.0 – 1.5 m away from the pollutant source; (2) using three identical cigarettes via smoking robots; (3) instruments such as SMPS and DustTrak were located outside the chamber, while instruments e.g. Tiger and C.A 1510 were placed on the top of the chamber, near the measuring ports; (4) before each individual measurement, the chamber were thoroughly ventilated to minimize the influence of previous measurements. This was ascertained by continuous monitoring of ultranet fine particle and $PM_{2.5}$ concentrations until they reached the concentration of background; (5) all instruments were zero calibrated. A mixing (standing) fan was placed next to the smoke robots in type 1 smoking tests to assist achieving a homogenized pollutant concentration in the chamber.

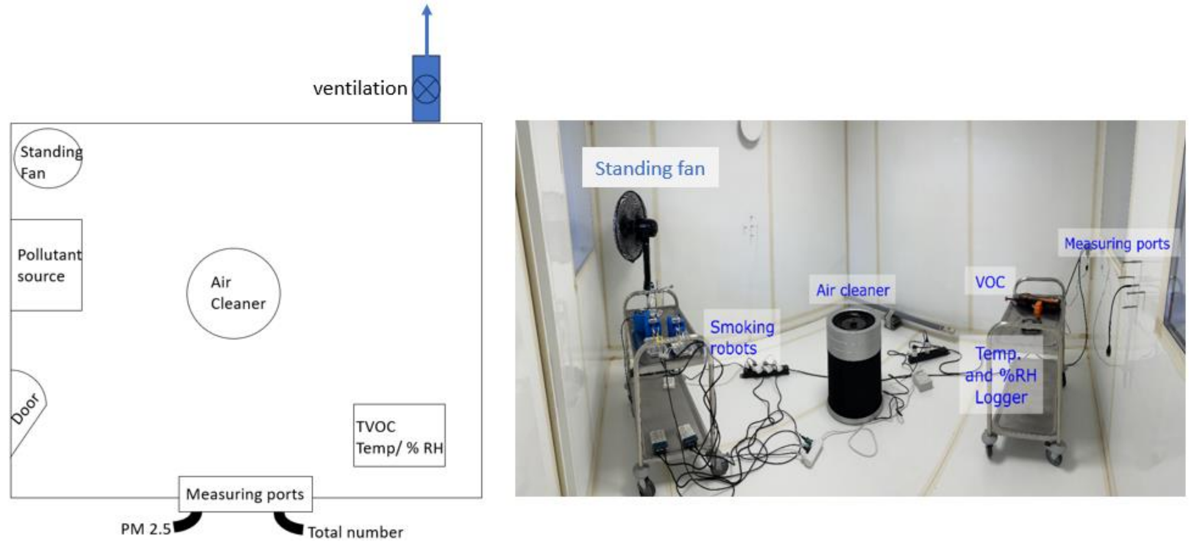

Figure 1 Sketch of placement of air cleaner, pollutant source, standing fan and sampling points in test chamber and a photo representing an example of facilities placement in a smoking test.

In smoking type 1 tests, the background concentration in the chamber was monitored for 10 minutes after the chamber was thoroughly ventilated and before the cigarettes were lit via the smoking robots which were automatically turned on from outside. When the entire cigarette was burnt out down to the white head, the smoking robots were turned off. The standing fan in the chamber was turned on for 10 minutes after no smoking was released from cigarettes. Last, the air cleaner was turned on at auto mode via APP installed in smart phone. The measured concentrations such as $PM_{2.5}$ and TOVC (if possible) by embedded sensors were recorded for minimum 30 minutes. However, there are two differences in smoking type 2 tests. The mixing fan was not used, and the air cleaner was turned on simultaneously when the cigarettes were lit. The overview of experimental cases is shown in Table 2.

Table 2 Overview of experimental cases

Air cleaner	**cases**	**Air cleaner**	**cases**	**Air cleaner**	**cases**
Air cleaner 1	Smoking, type 1	Air cleaner 3	Smoking, type 1	Air cleaner 1	Candles
	Smoking, type 1		Smoking, type 1	Air cleaner 2	Candles
	Smoking, type 2		Smoking, type 2	Air cleaner 3	Candles
Air cleaner 2	Smoking, type 1	Air cleaner 4	Smoking, type 1	Air cleaner 4	Candles
	Smoking, type 1		Smoking, type 1		
	Smoking, type 2		Smoking, type 2		

The set-ups of candle measurements were similar with those in smoking type 1 tests. The difference was that candles were lit manually after the concentration of the chamber background was monitored for 10 minutes. The concentrations of $PM_{2.5}$ and ultrafine particles were observed to be stabilized after 40 – 45 minutes. Then the air cleaner was turned on at auto mode for 30 minutes before it was switched to highest level of fan speed manually for another 30 minutes. Afterwards, the fan speed was switched back to auto mode again and the concentration of particles was monitored for another 30 minutes. Last, the candle was extinguished via blowing and the air cleaner was still on for 30 minutes, and the data of concentrations were kept logging, which are shown in section 3.

3 RESULTS & DISCUSSION

3.1 Comparison of $PM_{2.5}$ concentration between embedded sensors and DustTrak

Figure 2 and Figure 3 display the comparison of $PM_{2.5}$ concentrations measured by embedded sensor of air cleaner 1 and air cleaner 3, respectively, to those by DustTrak as examples of smoking type 1 tests. The results obtained from air cleaner 2 and air cleaner 4 were not shown because they have similar trends to results achieved from air cleaner 1 and air cleaner 3, respectively. The $PM_{2.5}$ concentrations measured by the embedded sensor were under-estimated for both air cleaner 1 and air cleaner 3 compared to the values measured by DustTrak. The embedded sensor could only detect the $PM_{2.5}$ concentration at maximum 500 µg m^{-3} and the concentration of $PM_{2.5}$ decayed immediately when air cleaner 1 was turned on. The embedded sensor of air cleaner 3 has detected $PM_{2.5}$ concentration at 1000 µg m^{-3} and $PM_{2.5}$ concentration was maintained at 1000 µg m^{-3} for a few minutes when it was higher than 1000 µg m^{-3} as indicated by DustTrak, shown in Figure 3.

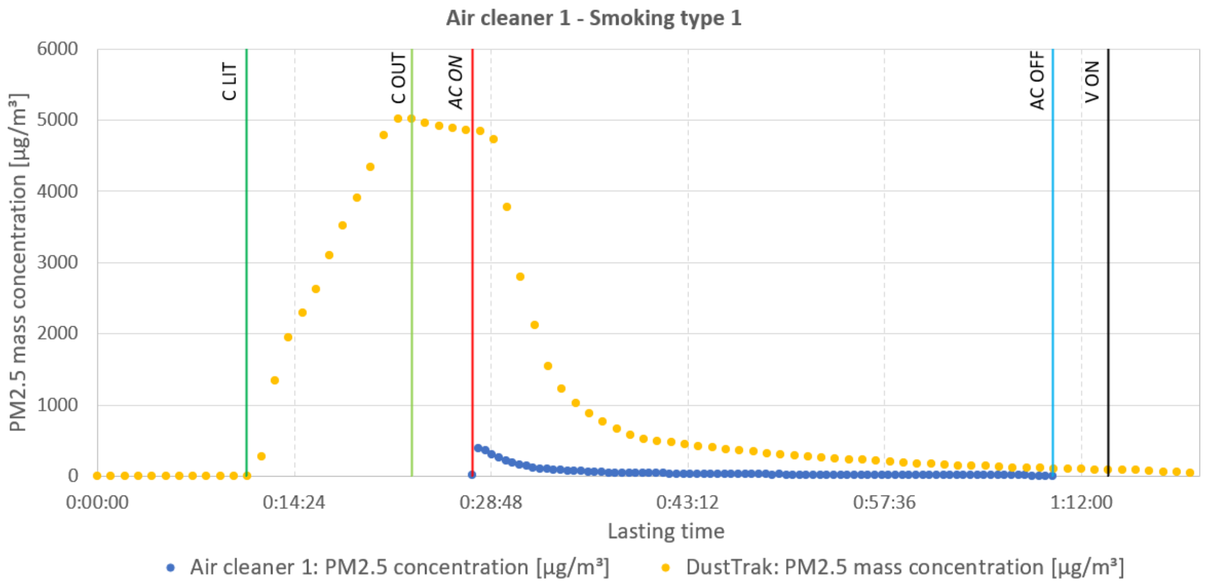

Figure 2 $PM_{2.5}$ concentrations of smoking type 1 test conducted with air cleaner 1. The abbreviations represent the changes through the experiment. C LIT: The cigarettes were lit, C OUT: no more smoke was observed from the cigarettes, AC ON: Air cleaner turned on, AC OFF: Air cleaner was turned off, V ON: the ventilation was turned on.

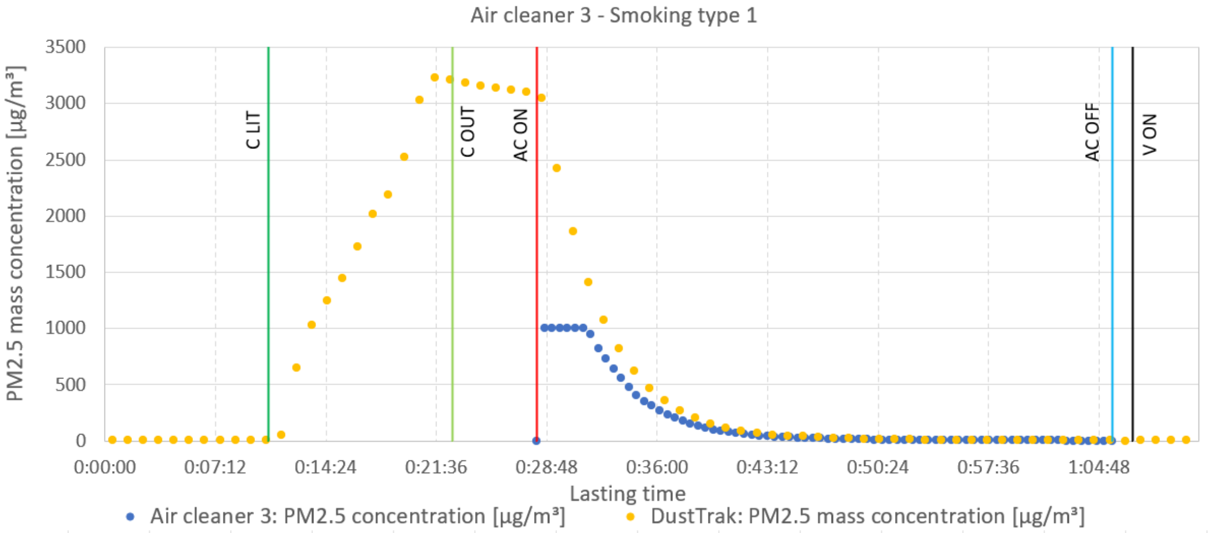

Figure 3 $PM_{2.5}$ concentrations of smoking type 1 conducted with air cleaner 3. The abbreviations represent the changes through the experiment. C LIT: The cigarettes were lit, C OUT: no more smoke was observed from the cigarettes, AC ON: Air cleaner turned on, AC OFF: Air cleaner was turned off, V ON: the ventilation was turned on.

These results indicate that the four air cleaner were able to remove $PM_{2.5}$ after they were turned on as the $PM_{2.5}$ concentrations were decayed, and they reached to a low level after 30 min for air cleaner 1 and after 15 min for air cleaner 3.

Smoking type 1 tests for each air cleaner were repeated, shown in Figure 4 for air cleaner 2 as an example. The recorded $PM_{2.5}$ concentrations were similar in two identical repeated measurements but slightly different during the period when $PM_{2.5}$ concentration declined. The fan speed changed at almost the same timestamps for air cleaner 1, 3 and 4 in the repeated tests. However, there was a 6 min delay for air cleaner 2 and the fan speed was changed to a low level at an almost identical $PM_{2.5}$ concentration measured by the embedded sensor in the two repeated measurements. A noticeable difference of $PM_{2.5}$ concentrations measured by DustTrak was observed when the fan speed of air cleaner 2 was changed. It seems that the $PM_{2.5}$ concentration measured by the embedded sensor of air cleaner 2 was not as stable as the other three air cleaner.

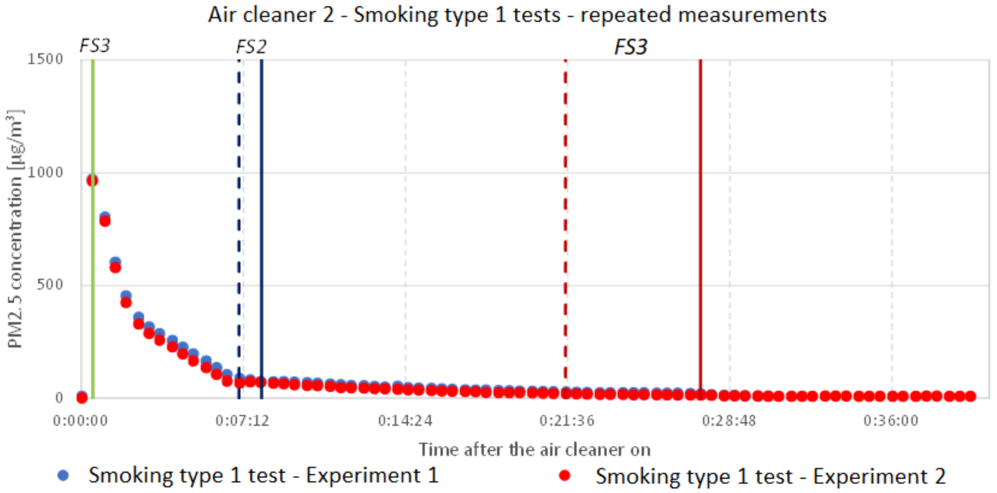

Figure 4 Comparison of $PM_{2.5}$ concentrations between two repeated measurements for air cleaner 2. The abbreviations stand for the level of fan speed (FS) that the air cleaner regulates.

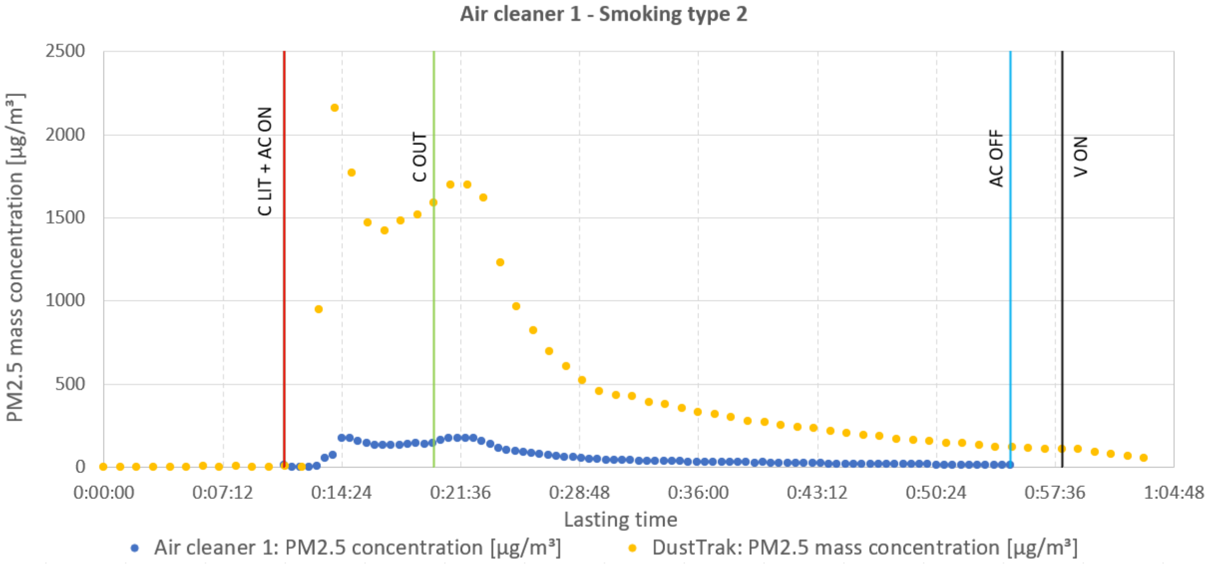

Figure 5 $PM_{2.5}$ concentrations of smoking type 2 test conducted with air cleaner 1. The abbreviations represent the changes through the experiment. C LIT: The cigarettes were lit, C OUT: no more smoke was observed from the cigarettes, AC ON: Air cleaner was turned on, AC OFF: Air cleaner was turned off, V ON: the ventilation was turned on.

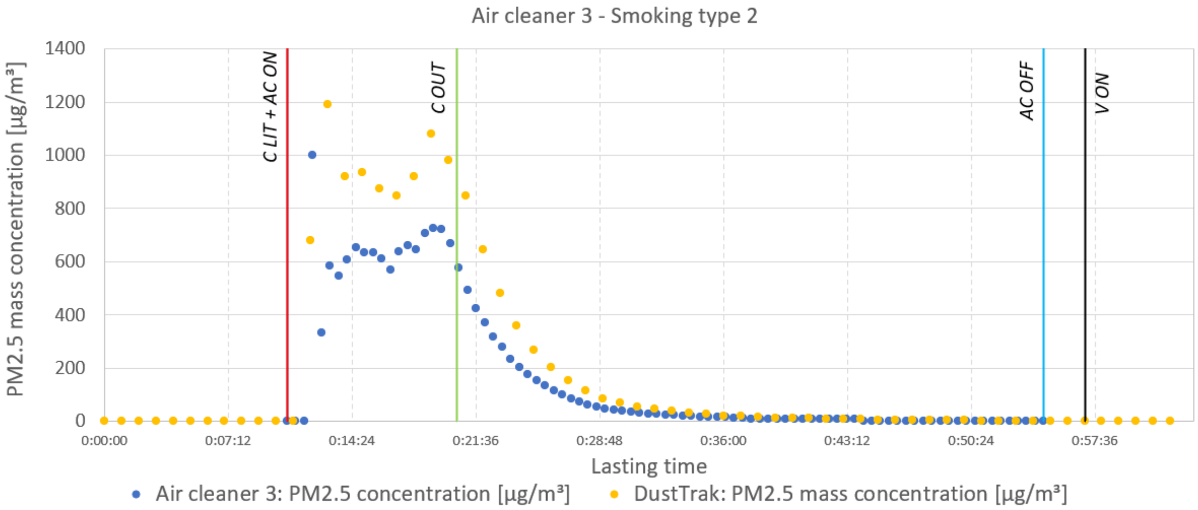

Figure 6 $PM_{2.5}$ concentrations of smoking type 2 tests conducted with air cleaner 3. The abbreviations represent the changes through the experiment. C LIT: the cigarettes were lit, C OUT: no more smoke was observed from the cigarettes, AC ON: air cleaner was turned on, AC OFF: air cleaner was turned off, V ON: the ventilation was turned on.

Figure 5 and Figure 6 show the comparison of $PM_{2.5}$ concentrations measured by the embedded sensors to those by DustTrak for smoking type 2 tests of air cleaner 1 and 3, respectively, when they were turned on simultaneously as the cigarettes were lit. Compared to $PM_{2.5}$ concentrations in Figure 2 and Figure 3, they were significantly lower in smoking type 2 tests. Turning on the air cleaner during the smoking is recommended per those results. Again, the $PM_{2.5}$ concentrations measured by embedded sensors were under-estimated for both air cleaner 1 and 3. The air cleaner 3 reduced the $PM_{2.5}$ concentration much faster than air cleaner 1 and the embedded sensor of air cleaner 3 seems also performing better than that of air cleaner 1. This could be an advantage in terms of exposure to relatively high level of $PM_{2.5}$ concentration in a short period.

3.2 Comparison of TVOC concentrations

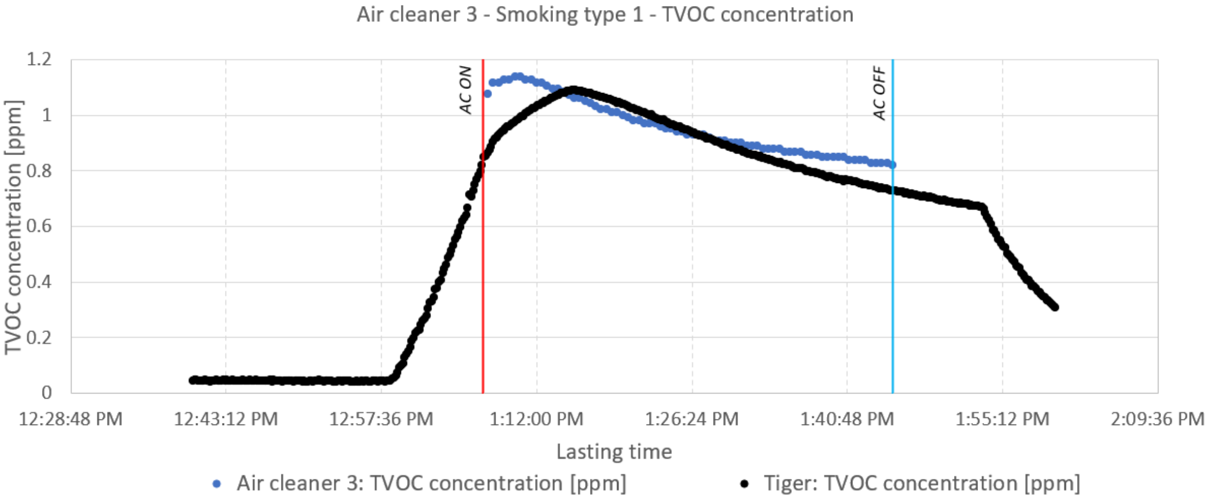

Figure 7 Variation of TVOC concentration for smoking type 1 test with air cleaner 3. The abbreviations represent the operation changes through the experiment. AC ON: air cleaner was turned on, AC OFF: air cleaner was turned off.

Figure 7 shows the variation of TVOC concentrations measured by embedded sensor and instrument Tiger in smoking type 1 tests for air cleaner 3. The measured TVOC concentrations by embedded sensor agreed well with those measured by Tiger and decayed when air cleaner 3 was turned on. The TVOC concentrations did not decay when air cleaner 1 and air cleaner 2 were turned on. But the TVOC concentrations measured by Tiger decreased as the air cleaner 3 and air cleaner 4 were turned on. Although the air cleaner 3 and air cleaner 4 did remove TVOC, the change of TVOC concentrations had little influence in regulating fan speeds.

3.3 Comparison of $PM_{2.5}$ concentrations in tests of candle burning

Figure 8 and Figure 9 show the variation of $PM_{2.5}$ mass concentrations and the total number concentration of ultrafine particles (total number concentration hereinafter) for air cleaner 1 and 4, respectively. The $PM_{2.5}$ concentration was relatively low in tests of burning candle, so the air cleaner was run at a low fan speed. The total number concentration was maintained at a stable level. After the fan speed was switched to the maximum level, the total number concentration was reduced significantly. A couple of fluctuations were observed when fan was run at the maximum speed. This could be explained by the fact that the maximum fan speed disturbed the candle flames and caused unstable burning of candles. After the fan speed was switched back to the auto-mode, the fan speed was switched to the low level and the total number concentration increased again as burning candle continuously released the ultrafine particles. The changes of fan speeds hardly impacted the $PM_{2.5}$ concentration. The extinguish of burning candle released particles with sizes larger than ultrafine particles size range so the mass concentration of $PM_{2.5}$ significantly increased. The air cleaner 1 reduced both $PM_{2.5}$ mass concentration and total number concentration. However, the fan speed was regulated mainly based on the $PM_{2.5}$ mass concentration. If total number concentration of ultrafine particles was critical under certain circumstances, auto mode of fan regulation is not preferred because it does not react to high total number concentrations.

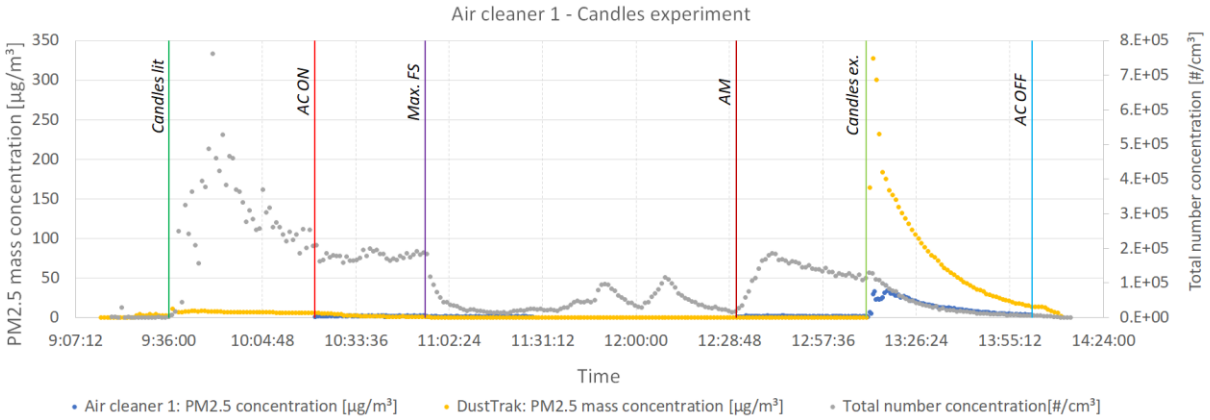

Figure 8 Total number concentration and $PM_{2.5}$ concentration with burning candles for air cleaner 1. The abbreviations represent the changes through the experiment. Candles Lit: The candles were lit, AC ON: air cleaner was turned on, Max FS: maximum fan speed level was employed, AM: auto mode was employed, Candles ex.: candles were extinguished, AC OFF: air cleaner was turned off.

When candles were extinguished, air cleaner 1 and 2 only perceived a small change in PM2.5 concentration. Consequently, the fan speeds were not adjusted. Air cleaner 3 and 4 did register the change in $PM_{2.5}$ mass concentration, as seen in Figure 9, and adjusted their fan speeds accordingly. The $PM_{2.5}$ mass concentration and the total number concentration were reduced quickly. This resulted in the $PM_{2.5}$ mass concentration in 10 $\mu g\ m^{-3}$ after the candles were blown out for 15 – 20 min. For air cleaner 1 and 2, it took about 40 minutes before the $PM_{2.5}$ mass concentration reached 10 $\mu g\ m^{-3}$. This extended time entail that the users of air cleaner 1 and 2 can be exposed to a higher level of particles for longer time, which is a risk of their health. Another observation from burning candle tests was that none of the air cleaner turned off automatically when the embedded sensors did not register $PM_{2.5}$ concentration. This could raise the concern to employ an air cleaner, which essentially consume electricity for no reasons.

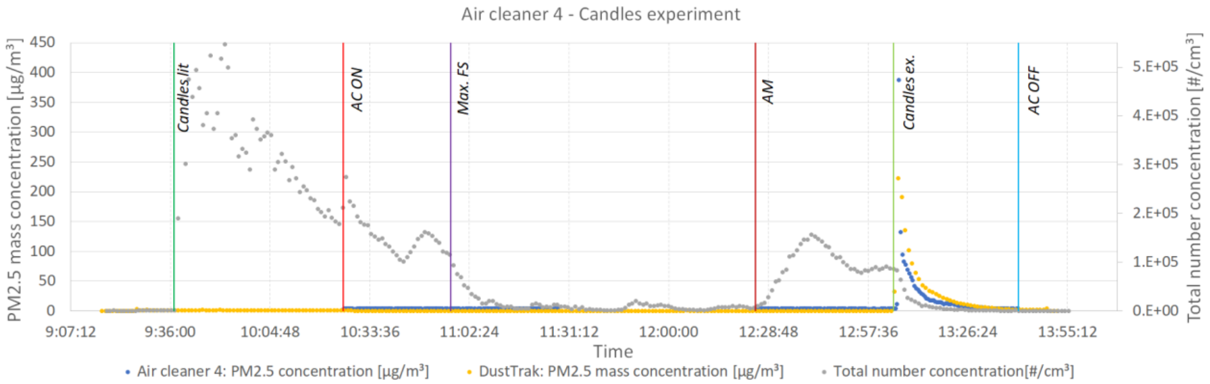

Figure 9 The result of the candles experiment conducted with air cleaner 4. The abbreviations represent the changes through the experiment. Candles Lit: The candles were lit, AC ON: Air cleaner turned on, Max FS: maximum fan speed level was employed, AM: auto mode was employed, Candles ex. Candles were extinguished, AC OFF: Air cleaner was turned off.

4 CONCLUSIONS

This study conducted experimental measurements in a climate chamber to assess the accuracy of embedded sensors of air cleaner and their influence on regulating fan speeds. Generally, the $PM_{2.5}$ concentrations were under-estimated by embedded sensors of air cleaner. The air cleaner can remove $PM_{2.5}$ when they were turned on in smoking tests and can also remove total particle concentration in burning candles tests with highest fan speed. It is recommended to turn on the air cleaner when the pollutant source of smoking is available instead of turning on the air cleaner after smoking. The customer should be reminded that the fan speed is not able to be regulated when the pollutant source is burning candles. The air cleaner being able to measure TVOC concentration cannot change its fan speed per TVOC concentration. This complete information might be suggested to be provided or the manufactory can add the feedback of TVOC concentration to fan speed regulation. It is also noticed that the embedded sensors of different air cleaner could perform diversely so standards to guide the test of air cleaner are beneficial in this industry. One of the limitations of this study is that the concentrations measured by the embedded sensors were recorded manually every 30 s. This should be improved in future studies. Little information of the embedded sensors such as the principles and types is provided, which makes more difficult to compare and discuss the results.

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