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# Gas phase air cleaning effects on ventilation energy use and indicators for energy performance

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## ABSTRACT

Gas-phase air cleaners can be used to either reduce occupant dissatisfaction for the same outdoor air flow rate or to reduce the outdoor air flow rate for the same resulting occupant satisfaction based on its clean air delivery rate (CADR). The latter lowers the required ventilation rate for the same indoor air quality and can thus lead to a reduction in energy use for preheating/cooling and from transporting the outside air. However, there is no current method or metric for determining the energy benefit of installing a portable air cleaner. This study aimed to establish a framework and metric for assessing air cleaner efficiency in relation to energy use. The investigated gas-phase air cleaner (GPAC) represented a stand-alone (portable) unit equipped with an active carbon filter. In order to evaluate the proposed metric human subject experiments were conducted to investigate the effect of a gas-phase air cleaner on perceived air quality. The purpose of the experiment was to determine the CADR as a function of the percentage of subjects dissatisfied. The experiments were complemented by building energy simulations which were used to estimate the annual energy use for heating, cooling, and transporting the outside air (fan energy). A CADR of approximately 50% (12 L/s) was identified when the pollution source was only represented by building emissions and a CADR of approximately 30% (9 L/s) was found when both bio-effluents and building emissions represented the pollution source. The proposed indicator, clean air efficiency (CAE), can be used to compare different solutions used for providing clean air into the space. Based on the results shown for an air handling unit (AHU) and a stand-alone GPAC for Copenhagen, Denmark - dominated by a high heating load - the GPAC was a viable solution, i.e. higher CAE, only if the AHU was not equipped with a heat exchanger. The GPAC was also more efficient if both bio-effluents and building emissions were present as pollution sources.

## KEYWORDS

KPI, air cleaner, ventilation, energy use, CADR

## 1 INTRODUCTION

Gas-phase air cleaning can be used to improve the Indoor Air Quality (IAQ) by removing gaseous pollutants with negligible effect on indoor $CO_2$ concentration (Zhang et al. 2011). They can be characterized by their clean air delivery rate (CADR), a measure for clean air delivery efficiency (Afshari et al. 2021).

A gas-phase air cleaner (GPAC) can be used to either reduce occupant dissatisfaction for the same outdoor air flow rate or to reduce the outdoor air flow rate for the same resulting occupant satisfaction based on its CADR. The former would lead to an improved air quality in polluted buildings (Bogatu, Kazanci, and Olesen 2021). The latter lowers the required ventilation rate for the same IAQ and thus reduces the energy use for preheating/cooling and from transporting the outside air (Bogatu et al. 2021; IEA EBC 2019).

Although air cleaners can be compared as a function of their ability to delivery clean air, i.e. as a function of their CADR, there is no current method or metric for determining the reduction in energy use obtained by installing a stand-alone air cleaner. This study aims to establish a framework and metric for assessing air cleaner efficiency in relation to energy use. The metric could potentially be used for comparing the effectiveness of an air cleaner relative to another method, e.g. all-air system, for transporting clean air into the space.

## 2 METHODS

In order to evaluate the proposed metric, human subject experiments were used to investigate the effect of a gas-phase air cleaner on the perceived air quality. The purpose of the experiment was to determine the CADR as a function of the percentage of subjects dissatisfied. The experiments were complemented by building energy simulations which were used to estimate the annual energy use for heating, cooling, and transporting the outside air (fan energy). The investigated GPAC represented a stand-alone (portable) unit equipped with an active carbon filter.

### 2.1 Clean air delivery rate

In the experiments, two scenarios were investigated, one where either both bio-effluents and building emissions or only building emissions were used as pollution sources (Hu 2023). Three human subjects were used as sources for bio-effluents and old linoleum as building emissions. The room temperature was 23 °C and the relative humidity (RH) was 50%. Experiments were made for outdoor air supply rates of 2.5, 4.0, 7.0, and 10.0 L/s per non-adapted person as recommended in EN 16798:1-2019 (CEN 2019). When human subjects were used as emissions sources and the air cleaner was employed, an outdoor air supply rate of 4 L/s per person was used while the number of stand-alone air cleaners was varied between one and three.

Two rounds of experiments were made, one with and one without the air cleaner. When in use, the air cleaner operated at the highest setting. During the experiments a panel of 37 subjects were asked to rate their acceptability through a whole-body exposure by entering the polluted rooms. Their characteristics and those of the subjects used for bio-effluent generation can be seen in Table 1. Their acceptability was rated using a continuous scale divided into two parts, from clearly not acceptable (-1) to just not acceptable (-0.01) and from just acceptable (0.01) to clearly acceptable (1).

Table 1. Human subject characteristics

| Column Title | Sensory assessment panel | Subjects used for bio-effluent generation |
|---|---|---|
| Total | 37 | 3 |
| Gender* | 23 males, 14 females | 2 male and 1 female |
| Age (mean ± SD) [years] | 25.3±3.3 | 25±3.3 |

*Sex considered binary, assigned at birth.

Prior to the experiment subjects were asked to get sufficient rest. They were not allowed to consume alcohol, garlic and spicy food in the evening, night before, or during the day of the experiment. Subjects were not allowed to consume caffeine within less than one hour prior to the experiment. Participants were asked to use odourless products during the course of the experiment and were asked to shower the prior evening. During the experiment, the three subjects used for generating bio-effluents entered the room one hour earlier before the panel assessed the indoor air quality.

For each air flow rate and round (with and without air cleaner), the percentage of subjects dissatisfied (PD), in %, was calculated as follows (Wargocki 2004):

$$PD = \frac{\exp(-0.18-5.28\cdot\overline{ACC}}{1+\exp(-0.18-5.28\cdot\overline{ACC})}\cdot 100\ \ [\%] \qquad (1)$$

Where $\overline{ACC}$ represents the mean acceptability rating made by the panel. The clean air delivery rate (CADR) was then determined as the percentage decrease in outdoor air flow rate for which the same PD was obtained with the air cleaner employed.

## 2.2 Energy use for heating, cooling, and ventilation

The annual energy use for heating, cooling, and transporting the outside air was estimated using a building energy model developed in IDA ICE (EQUA Simulation AB 2013) of an office space with an area of 19.8 $m^2$ and total volume of 53.46 $m^3$ (Bogatu et al. 2021). The office space had the same area and volume as the room employed in the experiments and was conditioned by an air-handling unit (AHU) consisting of an air-to-air counterflow heat exchanger (HEX), pre-heating and cooling coils, and supply and return fans. Two sets of simulations were made, one with and one without the HEX. A HEX effectiveness of 85% was assumed when the HEX was operating. The simulations were made using the IWEC2 climate data for Copenhagen, Denmark (IWEC 2001).

Except for an external wall having a 5 $m^2$ window, the office was assumed to be part of a multi-storey office building and thus surrounded by identical spaces. An external blind shaded the upper part of the window when the incident solar radiation on the outside of the glazing exceeded 100 $W/m^2$. A high level of airtightness was assumed and thus infiltration was zero. The internal heat gains consisted of two occupants (1.1 met), appliances with a long-wave radiation fraction of 0.5, and lighting with a convective fraction of 0.5. The occupants, appliances, and lighting amounted to a total internal heat load of 35.7 $W/m^2$. All internal heat gains were active on weekdays from 9:00 to 12:00 and 13:00 to 16:00.

A constant air volume (CAV) ventilation was used for conditioning the space. The AHU supply air temperature setpoint was 16 °C. Outside occupancy the air flow rate was set to 0.15 $L/(s\cdot m^2)$ while during work hours (9:00 to 16:00) the maximum air flow rate was 21 L/s or 28 L/s depending on the building type analysed, very low polluting (VLP) or low polluting (LP) (CEN 2019), respectively. An ideal heater and ideal cooler which operated only from 09:00 to 16:00 were installed in the office space to further condition the indoor thermal environment and maintain it between 20 °C and 26 °C.

In the simulations, the effect of a stand-alone air cleaner was analysed by reducing the maximum air flow rate proportional to the assumed clean air delivery rate (CADR). The annual energy use was determined for three CADRs (0%, 30%, and 50%) when the air cleaner was assumed to remove both bio-effluents and building emissions and one CADR of 50% when the air cleaner was assumed to remove only building emissions.

## 2.3 Air cleaner energy use

The annual air cleaner energy use was estimated from the power of the air cleaner and the total working hours. The total number of working hours during the simulation was 1560, assuming six work hours per day. At the setting used in the experiments for which the CADR was determined, the GPAC consumed 22 W. The same primary energy use factor of 1.9 was used for the electricity as in the simulation study (Bogatu et al. 2021).

## 2.4 Clean air efficiency

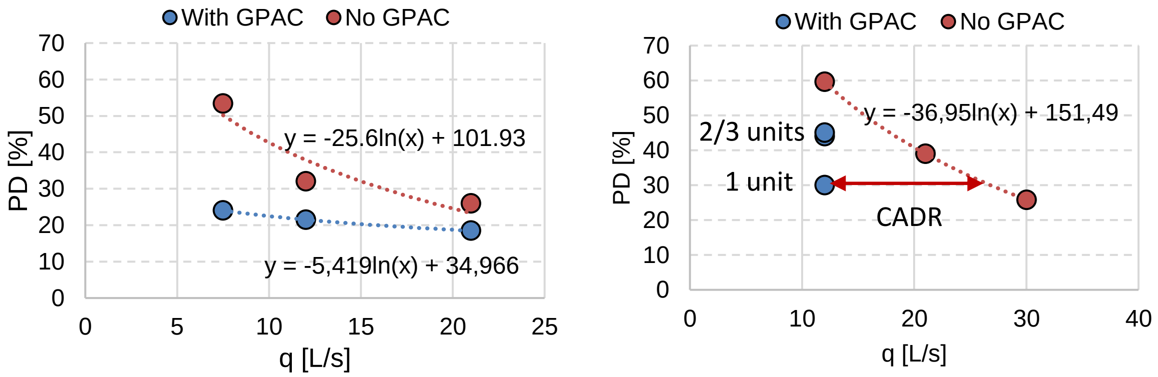
The clean air efficiency (CAE) is proposed as a key performance indicator (KPI) for comparing the efficiency of the AHU for heating, cooling, and transporting outdoor air and the efficiency of the stand-alone air cleaner for recirculating and cleaning the same amount of air. The CAE in L/s per kWh was calculated as the ratio between the CADR [L/s] and the energy used for providing that amount of clean air [kWh]:

$$CAE = \frac{\text{CADR}}{Energy\ use} \quad [\text{L/s per kWh}] \tag{2}$$

## 3 RESULTS

### 3.1 Clean air delivery rate

Figure 1 shows the relationship between the PD and the outdoor air flow rate (q) for the two scenarios analysed in the human subject experiments. As observed, no matter the pollution source, the air cleaner reduced the dissatisfaction rate for the same outdoor air flow rate. Moreover, Figure 1b shows that the outdoor air flow rate can be reduced if the air cleaner is employed for the same resulting dissatisfaction rate. The figure also shows that increasing the number of GPAC units did not improve the perceived air quality.



a) building emissions only b) bio-effluents and building emissions

Figure 1. Relationship between PD and outdoor air flow rate for the two scenarios analysed where the pollution source consisted of both bio-effluents and building emissions or building emissions only (PD: percentage of subjects dissatisfied, q; outdoor air flow rate).

From Figure 1a, where only building emissions were used as pollution source, it can be seen that a CADR of 50% (12 L/s) was obtained for a PD of 20% (Category II) which is the target Category for office buildings (CEN 2019). However, when both bio-effluents and building emissions were present as sources (Figure 1b), a PD of 20% was not achieved and the CADR varied as the number of air cleaners was increased, with an average value of 30% (9 L/s).

### 3.2 Energy use of AHU and air cleaner

Figure 2 shows the primary energy use of the AHU as a function of the CADR for the scenarios where the air cleaner removed both bio-effluents and building emissions obtained by Bogatu et al. 2021. Heating energy and the energy use for transporting the outside air (AUX) decreased as the CADR increased, while the cooling energy increased. Nevertheless, a linear relationship was found between the heating, cooling, and AUX energy use and CADR.

The heating energy use decreased when the HEX was operating. The HEX did not influence the cooling energy use, although it led to an increase in the AUX energy as the pressure drop in the AHU increased. The cooling energy use was however lower for the LP building type since the maximum required air flow rate was higher. Although not shown in the figure, as the resulting air flow rate was slightly lower when the air cleaner removed only building emissions for the same CADR (50%), the energy use for heating and transporting outdoor air decreased while cooling increased (Bogatu et al. 2021).

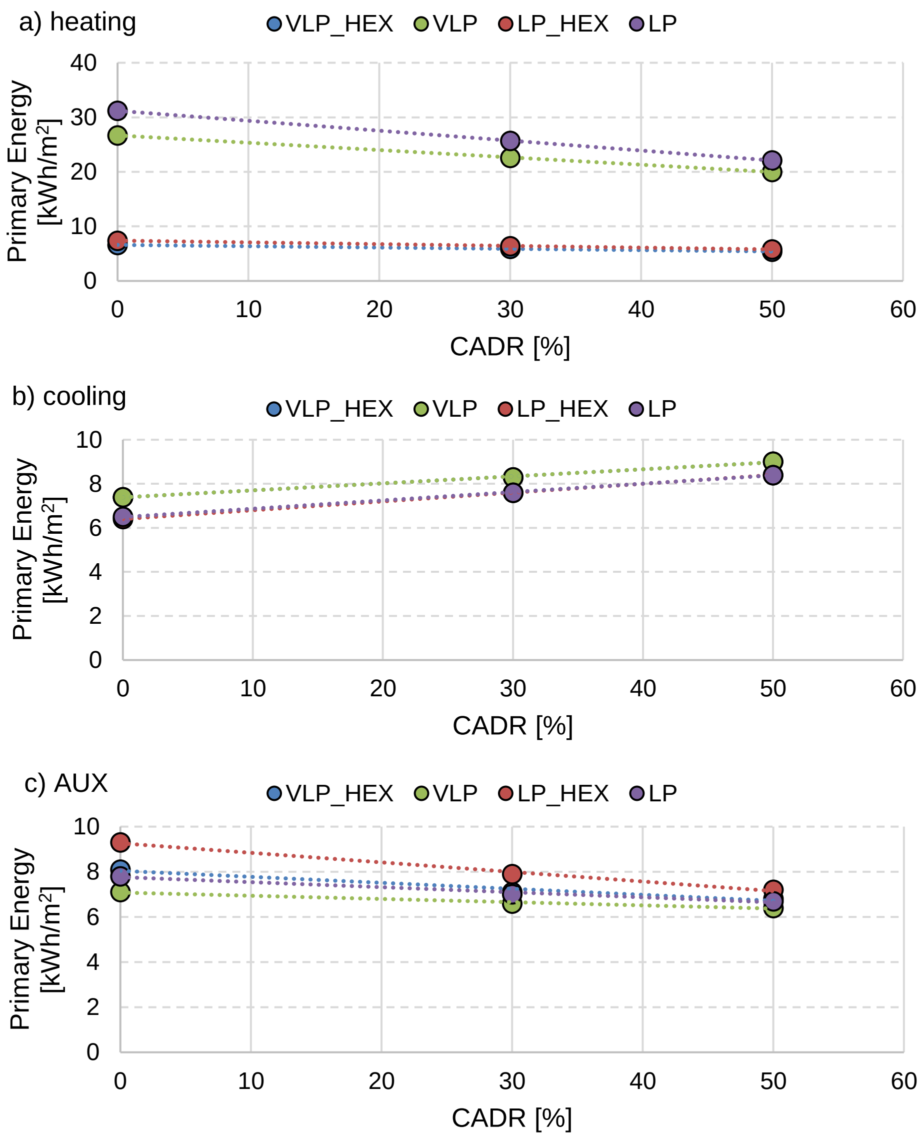


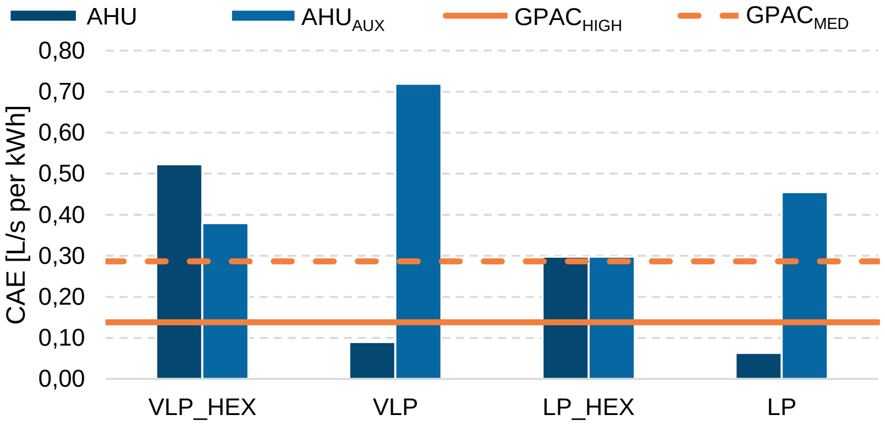
Figure 2. AHU primary energy use for heating, cooling, and transporting the outside air (AUX).

Assuming the GPAC ran at the highest setting for all working hours, its total energy use was estimated to be 3.3 kWh/m$^2$. This meant that the total energy use would increase by 3.3 kWh/m$^2$ in the scenarios where the GPAC was operating. However, at the medium setting (10.6 W) the total energy use would increase by only 1.6 kWh/m$^2$.

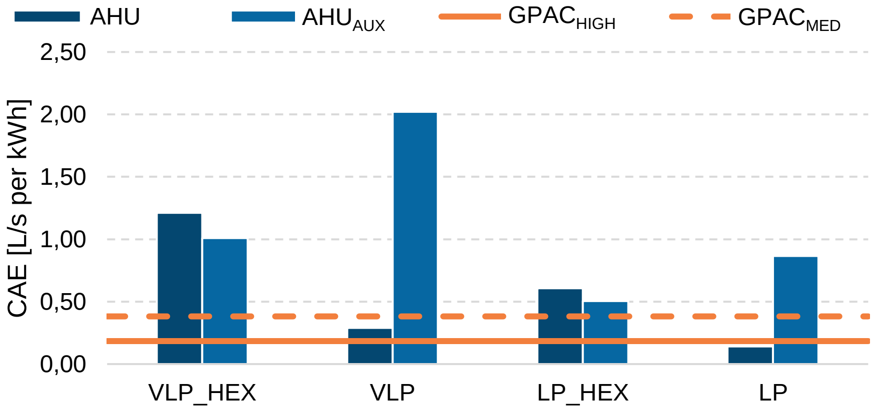
## 3.3 Clean air efficiency

The resulting CAE is shown in Figure 3 depending on the source of pollution. In the figure, the CAE of the AHU represented by bars is compared to the CAE of the GPAC represented by horizontal lines. The calculation was made for a CADR of 50% (12 L/s) when the air cleaner removed only building emissions and a CADR of 30% (9 L/s) when the air cleaner removed both building emissions and bio-effluents, as reported in section 3.1. The CAE values are given relative to the total annual AHU energy use (AHU), AHU fan energy use ($AHU_{AUX}$), i.e. AHU energy use without considering the energy use for heating and cooling the supplied air, energy used by the GPAC at high setting ($GPAC_{HIGH}$), energy use by GPAC at medium setting ($GPAC_{MED}$).

From the figure it can be seen that the CAE increases as less energy is used for supplying the respective clean air, 9 L/s in case of removal of both bio-effluents and building emissions and 12 L/s in case of removal of building emissions only. Thus, if the bar is higher than the horizontal line, the AHU should operate as less energy is used for heating, cooling, and transporting the outside air than for operating the GPAC.



a) bio-effluents and building emissions, CADR of 9 L/s



b) building emissions, CADR of 12 L/s

Figure 3. Clean air efficiency (CAE) relative to the total annual AHU energy use (AHU), AHU fan energy use (AHU$_{AUX}$), energy used by the GPAC at high setting (GPAC$_{HIGH}$), and energy use by GPAC at medium setting (GPAC$_{MED}$) by scenario.

For the investigated space and scenarios, the results show that the GPAC should be operated only when a HEX is not included in the AHU. When the GPAC removes only building emissions it may only lead to energy savings if the GPAC could be operated at a medium setting. The GPAC is never more efficient than simply supplying outdoor air if the energy use for heating and cooling the outdoor air is not taken into account as shown by the AHU$_{AUX}$ bars.

## 4 DISCUSSION

The experiments showed that the CADR of the gas-phase air cleaner (GPAC) varied depending on the pollution source, namely both bio-effluents and building emissions or only building emissions. Moreover, increasing the number of GPACs for the same room volume did not improve the perceived air quality. This requires further consideration as the room size and number of people were not varied. Thus, for a higher building volume and occupancy where spatial distribution may also influence particle, odour, and volatile organic compound (VOC) distribution, multiple air cleaners may be required to achieve a uniform indoor air quality.

Moreover, the air cleaner was only tested at the maximum setting. Further investigation is required if the same perceived air quality may be obtained at a lower setting or if the fan speed is varied between settings instead of running continuously, i.e. an improved control.

From the comparison made for Copenhagen, Denmark between the stand-alone air cleaner and the AHU, it was found that the GPAC could only save energy if employed in buildings where the AHU is not equipped with a HEX according to the clean air efficiency (CAE). In the simulations a constant supply air temperature setpoint of 16 °C was used while the space was equipped with ideal heater and cooler to cover the remaining load. An optimal control of the supply air temperature and the source for the room-side conditioning systems may further influence the energy use and thus the CAE.

Higher energy savings would be achieved if the energy use of the air cleaner could be decreased for the same resulting perceived air quality. The energy use varies though as a function of climate while primary energy factors vary as a function of the grid energy mix. These factors would thus influence the CAE of both the AHU and the GPAC. A higher electricity primary energy factor would make the GPAC less efficient while the primary energy use of the AHU would be further influenced by the source for heating and cooling and their respective primary energy factors. A warmer climate would reduce the effectiveness of the HEX (Bogatu et al. 2021) and would thus make the GPAC a viable solution.

## 5 CONCLUSIONS

From the experiments a CADR of approximately 50% (12 L/s) was identified when the pollution source was only represented by building emissions and a CADR of approximately 30% (9 L/s) was found when both bio-effluents and building emissions represented the pollution source. The assessed indicator, clean air efficiency (CAE), can be used to compare different solutions used for providing clean air into the space. Based on the results shown for AHU and stand-alone GPAC for Copenhagen, Denmark - dominated by a high heating load - the GPAC was competitive only if the AHU was not equipped with a heat exchanger. The GPAC was also more efficient if both bio-effluents and building emissions were present as pollution sources.

## ACKNOWLEDGEMENTS

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