

Gas-phase air cleaning effects on ventilation energy use and the implications of CO₂ concentration as an IAQ indicator for ventilation control

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Abstract

It is possible to use gas-phase air cleaning to improve the indoor air quality and reduce the energy use for ventilation. However, the energy implications of gas-phase air cleaners and the impact on the air quality are not yet quantified. Therefore, by using a dynamic building simulation, the impact of different clean air delivery rates on the energy use and indoor air quality were studied under different climatic conditions. The results show that air cleaners can reduce the energy use for conditioning and transporting the ventilation air by 1.9% to 18% while possibly reducing the pollution level of buildings. The amount of energy saved is however dependent on the boundary conditions of the system.

Key Innovations

- Energy use for conditioning and circulating the ventilation air can be reduced by installing air cleaners
- The amount of energy saved is dependent on climatic conditions, the type of HVAC system, and the energy use of the air cleaner itself
- Gas-phase air cleaners could be used to reduce the pollution level of a building while saving energy
- When designing demand control ventilation systems, the CO₂ concentration indicator must be adjusted according to the clean air delivery rate of the gas-phase air cleaner

Practical Implications

Although the simulation model was not validated, representative data was selected in order to obtain conclusive results. By simulating under different climatic conditions, results were obtained over a wide range of boundary conditions, thus further confirming the validity of the results.

Introduction

Gas-phase air cleaning can be used to improve the Indoor Air Quality (IAQ) by removing gaseous pollutants with negligible effect on CO₂ (Zhang, et al., 2011). This lowers the required ventilation rate for the same IAQ and thus

reduces the energy use for preheating/cooling and from transporting the outside air (IEA EBC, 2019). However, as the amount of outdoor air supplied to the spaces is reduced, the resulting CO₂ concentration will increase. This could have negative aspects on the air quality, especially where CO₂ concentration is used as an indicator for Demand Control Ventilation (DCV) (Olesen, Bogatu, Kazanci, & Coakley, 2020). This study aims to determine the impact of air cleaning technology on the CO₂ concentration as an IAQ indicator for control and evaluation according to present standards (Khovalyg, et al., 2020) and to quantify the resulting energy savings.

Methods

A dynamic building simulation model was developed using IDA ICE (EQUA Simulation AB, 2013). Airflow was supplied through a generic heating, ventilation and air conditioning (HVAC) system. Two sets of simulations were made, one with and the other without a heat recovery unit. The required air flow rate was determined according to Method 1, EN 16798-1:2019 (CEN, 2019) and adjusted according to the air cleaner's clean air delivery rate (CADR). Yearly simulations were run for different locations, i.e., Copenhagen (CPH), Denmark; Zürich (ZH), Switzerland; Palermo (PMO), Italy; and Tokyo (TYO), Japan and under two different building classes, low and very low polluting buildings according to CEN (2019).

Building model

The modelled building module consisted of two 19.8 m² office spaces with opposite orientations, South and North, connected by an 8.6 m² corridor. All spaces had a height of 2.8 m. The module was originally developed by Olesen and Dossi (2004) and was assumed to be part of a multi-storey office building with identical spaces around it. Except for the infiltration, the building envelope, internal heat gains, and external blind control were based on Kolarik et al. (2011) and Spitler (2014). The building construction had a thermal mass of 14 kJ/m². An external blind shaded the upper part of the window (2.7 m²) when the incident solar radiation on the outside of the glazing exceeded 100 W/m². Although the windows' U-value was not affected by the shading strategy, the visual transmittance and the solar gain factor were reduced by

9% and 14%, respectively. For the internal heat gains, the values recommended by CEN (2019) and ASHRAE (2013) for single office spaces and corridors were selected. Each office had two occupants (1.1 met), appliances with a long-wave radiation fraction of 50%, and lighting with a convective fraction of 0.5. The occupants (in total 11.8 W/m²), appliances (12 W/m²), and lighting (11.9 W/m²) amounted to a total internal heat load of 35.7 W/m². Lighting of 7.1 W/m² was the only heat gain present in the corridor, with the same convective fraction of 0.5. All internal heat gains were active on weekdays from 9:00 to 12:00 and 13:00 to 16:00 according to EN16798-1:2019. Infiltration was assumed to be zero as buildings are moving towards increased levels of airtightness (Vidal, Otaegi, & Oregi, 2020) (Danish Ministry of Transport, Building and Housing, 2020). This represents an extreme scenario where no additional airflow is provided to the enclosed space through leaks and cracks in the building envelope.

Gas-phase air cleaner

The gas-phase air cleaner was assumed to supply only clean air, i.e. no harmful by-products, and to be separated from the AHU, thus placed in the room as a stand-alone unit to recirculate the air. The gas-phase air cleaner was not physically implemented in the building model. Instead, to study its effect on heating and cooling energy use and indoor air quality, the total required air flow rate was reduced according to the air cleaner's CADR. In total, four different CADRs were selected, namely 0%, 30%, and 50% of the total required air flow rate, and one case where the air cleaner removed 50% of only the pollution from the materials in the building's interior (50% BP).

Air flow rate

Ventilation was supplied to all spaces with a constant air volume (CAV). The required air flow rate during occupancy was determined according to Method 1: Method based on perceived air quality from the EN16798-1:2019 standard. According to EN16798-1:2019, the total ventilation rate for the breathing zone is:

$$q_{tot} = n \cdot q_p + A_R \cdot q_b \quad (1)$$

where n is the design value for the number of persons in the room, q_p is the ventilation rate for occupancy per person in L/(s·person), A_R is the floor area in m², and q_b is the ventilation rate for emissions from building in L/(s·m²). In order to incorporate the effect of the air cleaner, the ventilation rate (q) was adjusted by the CADR. If both bio effluents and building emissions were removed equally by the air cleaner (scenarios 0%, 30%, and 50%), the total ventilation rate was reduced according to equation 2 by the appropriate CADR. On the other hand, the required air flow rate where only the building emissions were removed by the air cleaner (scenario 50% BP) was calculated according to equation 3.

$$q = (1 - CADR) \cdot q_{tot} \quad (2)$$

$$q = n \cdot q_p + (1 - CADR) \cdot A_R \cdot q_b \quad (3)$$

In all scenarios the aim was to achieve a Category II EN16798-1:2019 IAQ, which corresponded to an expected dissatisfaction of 20% of total occupants. For the

ventilation rate for occupancy per person, q_p , the Category II EN16798-1:2019 value for non-adapted persons was used. The ventilation rate for emissions from building, q_b , was selected for Category II depending on the scenario according to EN16798-1:2019, i.e., for low and very low polluting buildings. In the standard, these values are found categorized depending on the pollutant (e.g. volatile organic compounds, formaldehyde) emission rate of the majority of interior materials. No matter the resulting total ventilation rate, a minimum of 4 L/(s·person) was kept as recommended by EN16798-1:2019.

Outside occupancy, the minimum recommended air flow rate for diluting building emissions according to EN16798-1:2019, 0.15 L/(s·m²), was set. The same air flow rate, 0.15 L/(s·m²), was also supplied continuously over the entire day in the corridor connecting the two offices.

Air handling unit model

The generic IDA ICE air-handling unit (AHU) consists of an air-to-air counterflow heat exchanger (HEX), pre-heating and cooling coils, and fans (Figure 1). When the HEX was part of the AHU, the heat exchanger effectiveness was set to 85%, as required in the Danish building regulation for 2020 (Danish Ministry of Transport, Building and Housing, 2020). Filters were not present in the model. However, the total energy use for supplying air into the building was determined as a function of the total pressure drop over the AHU, a parameter of the supply and exhaust fans.

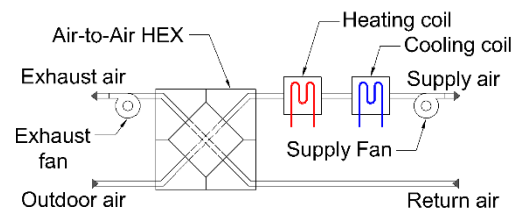


Figure 1. Air handling unit model.

In order to obtain reliable information from the model, the data used for the simulation was taken from an air handling unit product available on the market. The selected unit was a compact air handling unit with a counterflow heat exchanger and a cooling/heating coil capable of supplying an air flow rate between 90 and 620 m³/h (EXHAUSTO, 2021). An external pressure drop of 200 Pa was assumed for the ducting system dimensioning (approximately 60 m length straight duct of 0.25 m diameter). (F9) epM1 80% filters were selected on both the supply and exhaust lines of the AHU. This was done to obtain the maximum pressure drop across the AHU. Based on the required air flow rate, the total fan pressure rise and efficiency were determined using the online design tool of the manufacturer (EXHAUSTO, 2021). In the second set of simulations, since the AHU did not have a heat exchanger, the HEX efficiency was set to 0%. Moreover, the static pressure introduced by the heat exchanger was deducted from the system's total pressure drop. The resulting total pressure drop was implemented in the model while maintaining the same fan efficiency.

Control

Air was supplied by the AHU at a constant air volume, q , on weekdays from 09:00 to 16:00 and at the minimum recommended air flow rate, $0.15 \text{ L}/(\text{s}\cdot\text{m}^2)$, otherwise. For simplification purposes, the air handling unit supply air temperature setpoint was 16°C . Moreover, by defining the supply air temperature setpoint locally in the AHU the control strategy ensured that the AHU did not heat or cool the air when not needed. If the outdoor air was lower than the supply temperature setpoint, heat was recovered from the extract air if possible. Cooling took place in the heat exchanger if the outdoor air was higher than the supply air setpoint and the extract air was lower than the outside air. The heating and cooling coils further conditioned the supply air after the heat exchanger if needed to ensure the supply air temperature, 16°C , was maintained.

An ideal heater and an ideal cooler were installed in each office space, which operated only from 09:00 to 16:00. The ideal heater and cooler were used to maintain a constant indoor thermal environment across scenarios while providing the required heating and cooling energy. The ideal heater and cooler ensured that a Category II (EN1698-1:2019) indoor thermal environment was maintained in the two offices. Their operation was based on the simplified outdoor running mean temperature (T_{rm}). The running mean temperature was determined according to EN16798-1:2019, as a weighted average of the daily mean outdoor temperature of the previous 7 days. The operative temperature setpoints were the Category II limits, 20°C for the ideal heater and 26°C for the ideal cooler. The ideal heater and cooler maintained

the operative temperature between the heating and cooling setpoints for a running mean temperature between 10 and 15°C . Only the ideal heater operated for a running mean temperature below or equal to 10°C , ensuring a minimum operative temperature of 20°C . For a running mean temperature above or equal to 15°C only the ideal cooler operated with a setpoint of 26°C .

Results

Outdoor environment

For the simulations the IWEC2 climate data was used (ASHRAE, 2013). Figure 2 shows the daily mean outdoor air temperature and Figure 3 the outdoor absolute humidity in the four cities analysed. As observed, the lowest daily mean outdoor temperatures and absolute humidity levels were registered in Copenhagen and Zürich over the entire simulated year. The outdoor humidity levels were the highest over the year in Palermo, where the highest daily mean outdoor air temperatures were also registered. Tokyo was situated in between the other three cities, with high outdoor temperatures and absolute humidity levels during summer, spring, and autumn. During the winter months, December, January, and February, the absolute humidity and outdoor air temperatures were however closer to the values registered in Copenhagen and Zürich.

Air flow rate

The resulting air flow rates during occupancy for one office space are given in Table 1. The two offices had the same air flow rates since both had the same area and number of occupants. In the table, values are provided for

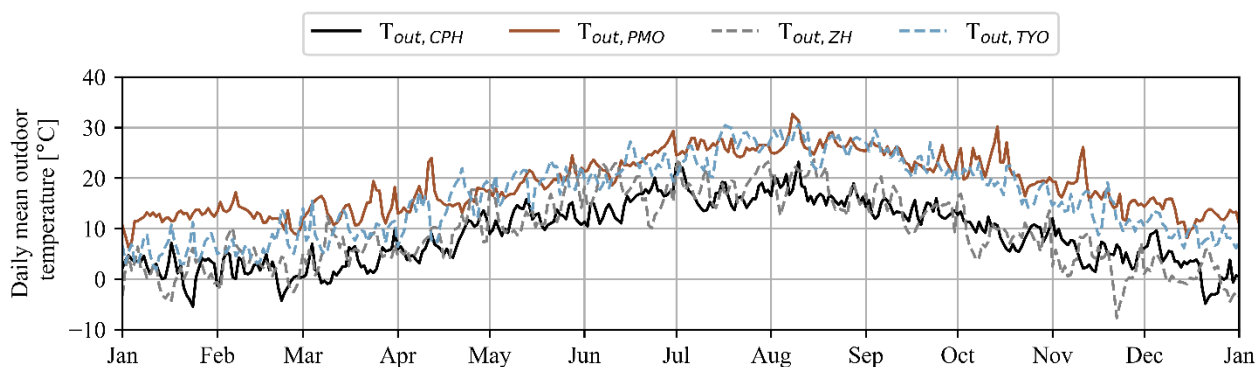


Figure 2. Daily mean outdoor air temperature in the three cities analysed, Copenhagen (CPH), Palermo (PMO), Zürich (ZH), and Tokyo (TYO).

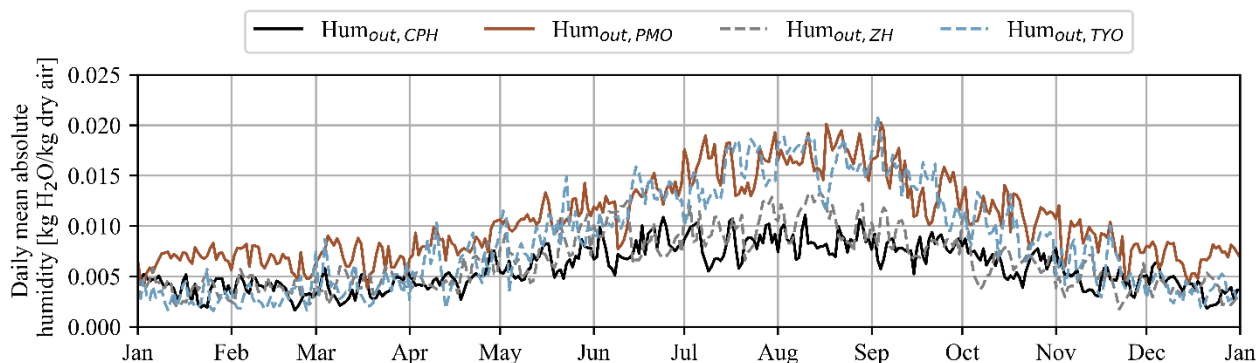


Figure 3. Daily mean outdoor absolute humidity for the cities analysed, Copenhagen (CPH), Palermo (PMO), Zürich (ZH), and Tokyo (TYO).

each clean air delivery rate and according to the building pollution level.

Table 1. Total required air flow rates during occupancy for one office space (VLP/LP: very low/low polluting).

CADR	$q_{tot,VLP}$ [L/s]	$q_{tot,LP}$ [L/s]
0%	20.93	27.86
30%	14.65	19.5
50%	10.47	13.93
50% BP	17.47	20.93

The highest required air flow rate was registered when the gas-phase air cleaner was not operational (CADR 0%). As the CADR increased, the required air flow rate decreased. The required air flow rate was higher in the 50% BP scenario than in the 50% one since only the building emissions were reduced by the air cleaner as opposed to the emissions from both people and the building.

Indoor thermal environment

As the main focus of this study was the indoor air quality and the effect of the air cleaner on the energy use, little detail was set on the thermal conditioning systems in the two office rooms. Therefore, the two ideal heating and cooling systems were only implemented to obtain an estimate of the required energy for conditioning the building module according to the outdoor climate. Nevertheless, the ideal heaters and coolers maintained the indoor thermal environment within the selected limits over the entire year according to the control.

Energy use

Figure 4 shows the primary energy use for heating, cooling, and transporting the ventilation air (fan energy) with and without a heat exchanger present in the air handling unit. The values are provided according to the city, building pollution level, and clean air delivery rate. The primary energy factors used were 1.9 for electricity and 1 for heating, as recommended by the Danish Ministry of Transport, Building and Housing (2020).

The results show that as the air cleaner's CADR increased, the total primary energy use for heating decreased as less air passed through the air handling unit. This is visible for all cities and both building pollution levels. However, reducing the required air flow rate had a higher impact on the primary heating energy use in cold climates (Copenhagen and Zürich), as more heating energy was saved from one scenario to another. Nevertheless, by adding the heat exchanger in the air handling unit the heating energy use reached values close to 0 kWh/(m²·year) in the hot climates of Palermo and Tokyo due to the high efficiency of the heat exchanger and the infiltration which was assumed to be zero.

The primary energy use for cooling registered little to no difference between the cases with and without heat exchanger. In cold climates such as Copenhagen and Zurich, the cooling energy increased with an increase in the CADR as less cooling was provided by the air handling unit. Therefore, the indoor units had to cover the remaining load. On the other hand, for Palermo and Tokyo, a decrease in the primary energy use for cooling

was registered since less air had to be conditioned by the air handling unit for an increase in the CADR.

The primary energy use required for delivering the required air flow rate to the offices, i.e. the fan energy, decreased for an increase in the clean air delivery rate of the gas phase air cleaner. Nevertheless, the required primary energy use increased when the heat exchanger was present in the system as the pressure drop in the air handling unit was higher.

Table 2 shows the energy savings resulting from the reduction in the required air flow rate compared to the reference case (CADR 0%). Greater energy savings were obtained in low polluting than very low polluting buildings. Moreover, the most energy savings were obtained when the HEX was not part of the AHU with up to 14.1% in very low polluting buildings and up to 18.2% in low polluting buildings, however dependent on the climate. On the other hand, when the heat exchanger was part of the system energy savings of maximum 9.5% were obtained.

Table 2. Energy savings for the scenarios analysed (VLP/LP: very low/low polluting building).

Scenario		Saved energy [%]					
		30%		50%		50% BP	
		VLP	LP	VLP	LP	VLP	LP
CPH	HEX	3.6	5.2	4.1	7.4	2.3	4.3
	-	9	11.4	14.1	18.2	5.1	9.5
PMO	HEX	2.8	4.7	4.2	6.5	1.9	4.1
	-	3.3	5.3	5.1	7.6	2	4.4
ZH	HEX	3.8	6.3	5.5	9.5	2.1	5.2
	-	8.9	11	14	17.5	5.1	9
TYO	HEX	3.7	5.8	5.3	8.6	2.4	5.1
	-	5.5	7.8	8.6	12.1	3.1	6.7

In terms of location, the highest energy savings, were registered in Copenhagen (between 2.3% and 18.2%) and Zürich (between 2.1% and 17.5%). The least energy savings were registered in Palermo, between 1.9% and 7.6%. With the highest reduction of air flow rate (50% CADR), the module registered energy savings between 4.1% and 18.2%. Nevertheless, even with a 30% reduction in the total required air flow rate, energy savings between 2.8% and 11.4% were obtained. However, a reduction in the required air flow rate associated with the building emissions (50% BP) led to the least energy savings, between 1.9% and 9.5%.

Indoor air quality

Since the same air flow rate was supplied to each office, the indoor air quality in the two offices was identical. Therefore, for the analysis, only the South office was presented. Figure 5 shows the absolute CO₂ concentration distribution (400 ppm outdoor CO₂ concentration) over the investigated year for each clean air delivery rate according to the building pollution level. Moreover, two Category II limits are presented, the default design CO₂ concentration (Method 2: based solely on emissions from people, EN16798-1:2019) and the one calculated according to the required air flow rates determined using Method 1 from the same standard.

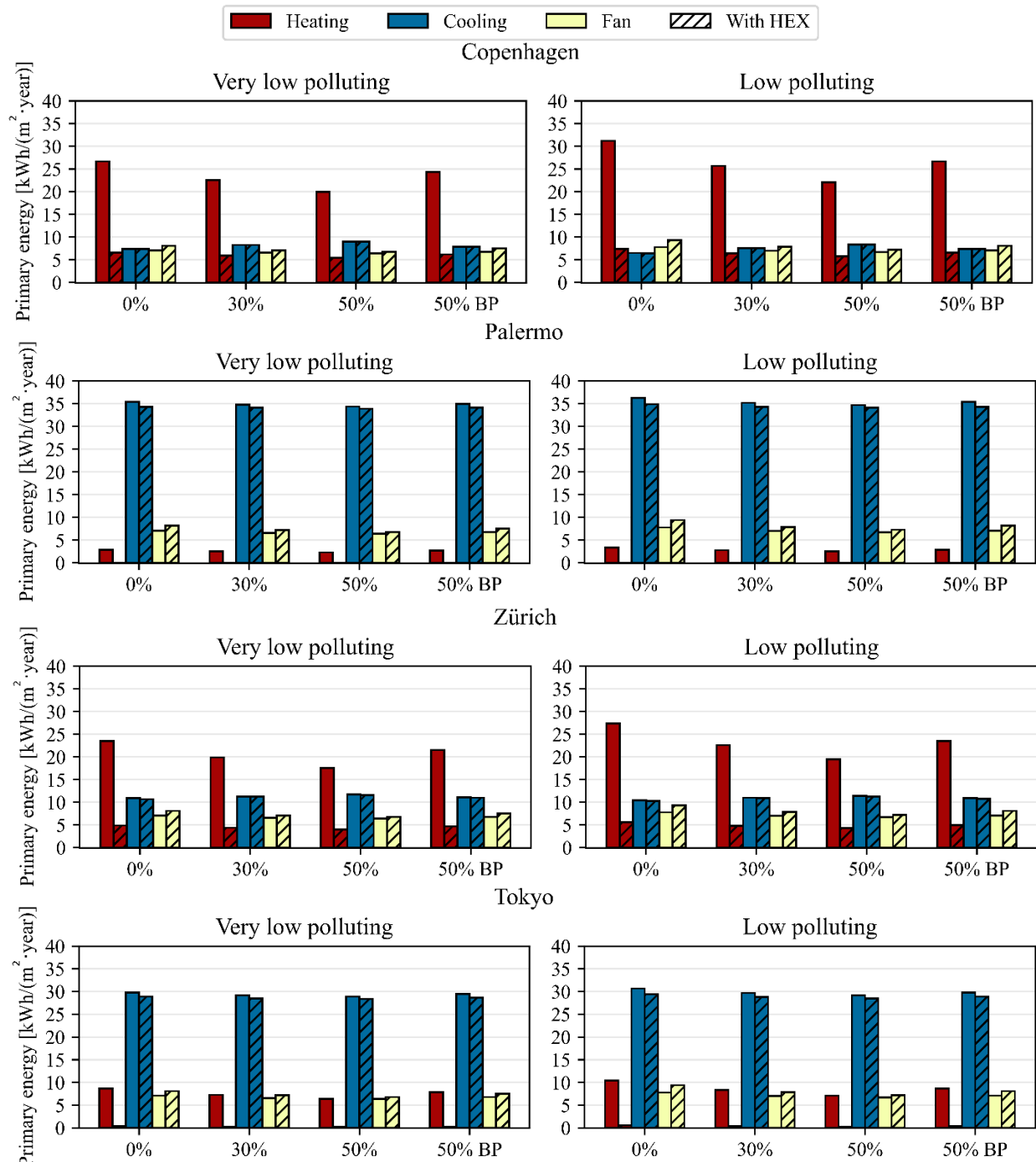


Figure 4. Primary energy use for each CADR value by building type, Very low polluting and Low polluting, with and without heat exchanger for the locations analysed (50% BP: 50% CADR of only the building emissions).

It can be observed that the CO₂ concentration was always within the determined limits using the required air flow rates calculated with Method 1. Moreover, lower CO₂ concentrations were registered in the low polluting building scenario since a higher required air flow rate was used for removing the emissions from the building, q_b . Nevertheless, since the determined air flow rate for a CADR of 50% in the very low polluting building scenario (5.3 L/s/person) was lower than the Category II default air flow rate (7 L/s/person), the CO₂ concentration exceeded the default limit for approximately 25% of the occupied time in that case in Copenhagen, Palermo, and Tokyo. In

the same scenario, CO₂ concentrations higher than the default limit were registered in Zürich for slightly more than 25% of the occupied time. However, in Zürich the CO₂ concentrations over the year were overall higher compared to the other cities analysed, since the amount of air decreased due to the higher altitude while the generated CO₂ by the occupants remained constant.

Relative humidity

Figure 6 shows the relative humidity during occupancy for the two building pollution levels for all CADRs investigated. The relative humidity never registered levels above the Category II upper limit of 60% as defined by

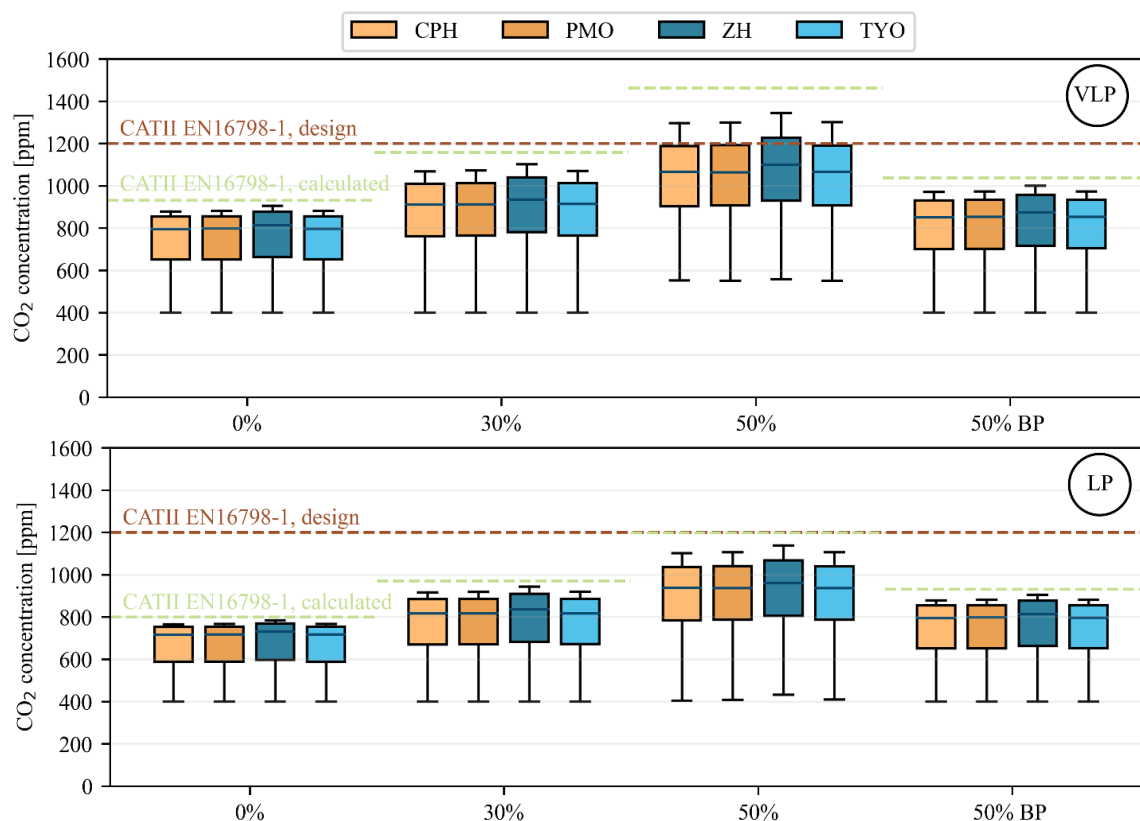


Figure 5. Absolute CO₂ concentration in the South oriented office for very low polluting (VLP) and low polluting (LP) buildings during occupancy.

EN16798-1:2019. Nevertheless, relative humidity levels below 25%, lower limit of Category II in standard EN16798-1:2019 were registered in all locations. The maximum time below the limit, 25% of the occupied time, was registered in Tokyo. Moreover, relative humidity levels concentrated towards the upper limit, 60%, were obtained in the humid climate of Palermo.

No significant difference was observed between the scenarios with and without the heat recovery unit since no humidity exchange was possible between the supply and return airflows. However, when the heat exchanger was added the process developed slightly different on the psychrometric chart. As heat exchange occurred in the recuperative heat exchanger without condensation in certain cooling instances, the air entered the cooling coil at a lower temperature than in the scenarios where the heat exchanger was not present. Therefore, although at the same temperature, the air after the heat exchanger had slightly different humidity levels.

Discussion

The results show that depending on climate energy savings between 1.9% and 18.2% could be achieved by using an air cleaner to substitute part of the total required air flow rate. These savings are achieved by reducing the energy use for heating, cooling, and transporting the ventilation air. Additional energy savings would also be obtained from the reduction in pumping power, however negligible compared to the fan power.

The amount of energy saved is dependent on the presence of a heat exchanger in the AHU, which preheats and

precools the outside air. As shown in Table 2, a reduction of the supply air flow rate led to energy savings as less air had to be conditioned by the heating and cooling system. However, reducing the supply air flow rate had a higher effect when the heat exchanger was not present in the AHU, since the air was never preheated or precooled. This effect was higher in cold climates such as Copenhagen and Zürich since a great amount of energy was used for heating the ventilation air during the heating season and transition periods (Figure 2 and Figure 4). On the other hand, in hot climates such as Palermo and Tokyo, although increasing the CADR saved energy, the difference between the scenarios with and without heat exchanger was negligible since in those climates cooling was predominant which was almost constant.

The primary energy use for transporting the air is however influenced also by the total pressure drop in the air handling unit. According to Zhang et al. (2011) the energy use of air cleaner energy use is often overlooked although critical when investigating the obtained energy savings from heating, cooling, and transporting the ventilation air. In this study, the air cleaner was assumed to be separate from the AHU and placed inside each office as a stand-alone unit. Therefore, the pressure drop over the air cleaner was not taken into consideration in the AHU. Nevertheless, the air cleaner could also be placed directly in the air handling unit, either directly on the supply to reduce harmful pollutants from the outside air, or on the return, to allow the recirculation of air without the risk of contaminating the supply air. The aforementioned placements of the air cleaner would therefore have an

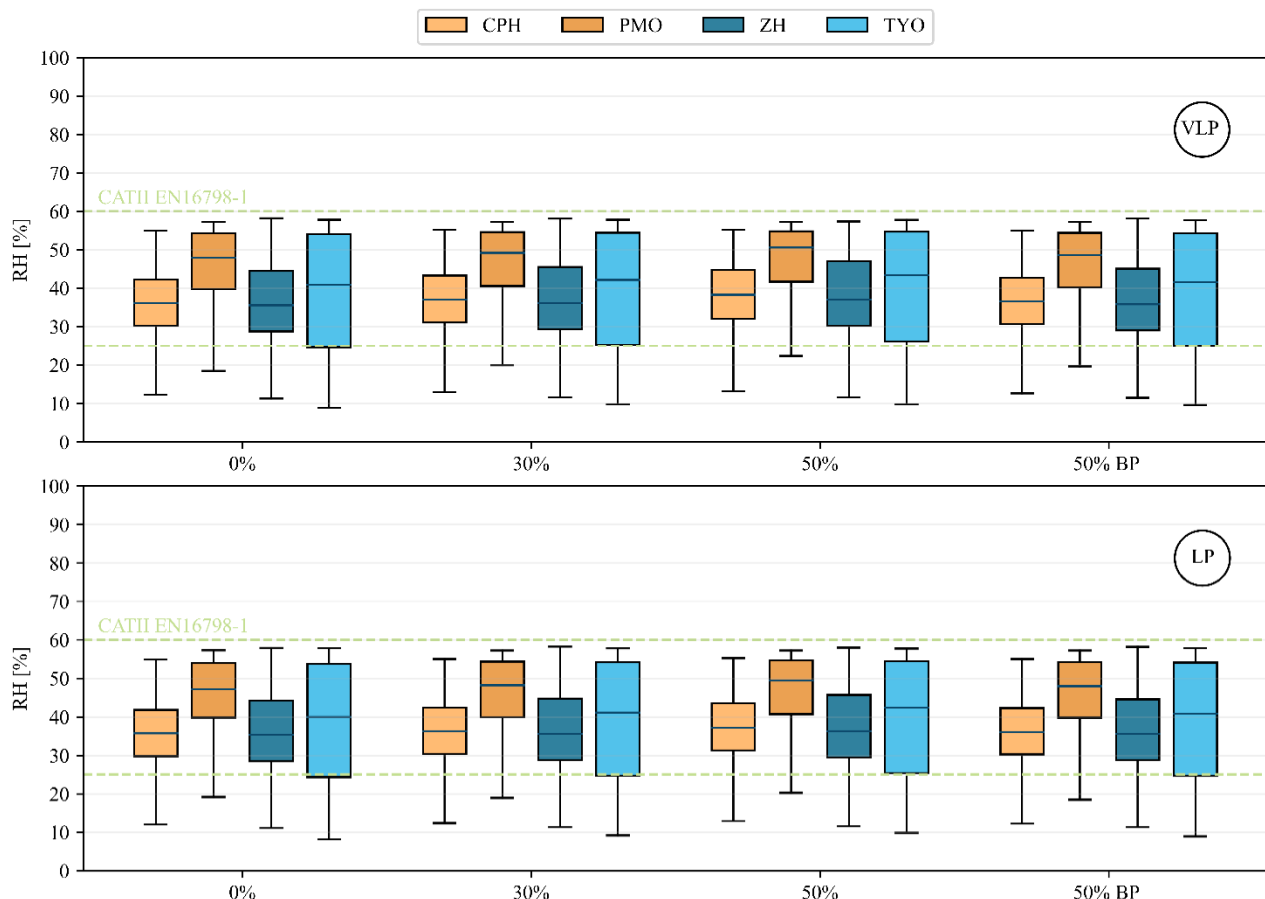


Figure 6. Relative humidity (RH) for very low polluting (VLP) and low polluting (LP) scenarios during occupancy.

impact on the total pressure drop in the AHU, increasing it. As a consequence, a higher auxiliary energy use (fan energy use) would be obtained. Moreover, even for a stand-alone placement as the one assumed, additional energy use would be registered by the air cleaner for recirculating the air. Depending on the air cleaner technology, for the investigated CADRs a power usage between 50 to 100 W can be expected (United States Environmental Protection Agency, 2018) (SODECA, 2020).

By looking at the total required air flow rate determined for the scenarios analysed (Table 1) it can be observed that the same required air flow rate could be obtained between two different building pollution levels (scenarios 0%, very low polluting buildings and 50% BP, low polluting buildings). Thus, the same indoor air quality and energy use (without including air cleaner energy use) could be achieved for two different building pollution levels if an air cleaner with a sufficient CADR would be installed in the more polluting building. This is further visible in Figure 4 and Figure 5 where the same primary energy use and CO₂ distribution were obtained for the two aforementioned scenarios across all climates.

The resulting CO₂ concentration (Figure 5) and its limits varied between the investigated CADRs (Method 1 calculated limits). As mentioned by Olesen et al. (2020) this could present an issue for systems with demand control ventilation (DCV) where the CO₂ concentration is used as an indicator. If an air cleaner is added or the

CADR of the air cleaner changes over time (e.g. changing the air cleaner or due to particle accumulation), the CO₂ concentration setpoint must be adjusted accordingly to reach the same indoor air quality.

The CO₂ concentration was also higher than the default limits (Method 2) for a CADR of 50% in the very low polluting building scenario for all climates. Although far from any health limit and with positive effects on the energy savings, it could potentially pose an issue for the perceived air quality, health, or work performance of occupants if the CADR is further increased (Olesen, Bogatu, Kazanci, & Coakley, 2020) (Fisk, Wargocki, & Zhang, 2019). Additionally, gas-phase air cleaners may generate harmful by-products (Zhang, et al., 2011). Thus, more conclusive results are required from human subject experiments in order to draw a definite conclusion and to identify other relevant IAQ indicators. Moreover, for all other CADRs the CO₂ concentration was actually lower than the default value recommended by EN16798-1:2019. Therefore, as pointed out by Olesen et al. (2020), by taking into consideration the building pollution level on top of people emissions (Method 1) a different air quality will be obtained than by only using the people emissions (Method 2).

A relative humidity (RH) below 25% (Category II EN16798-1:2019) occurred mostly in the heating season and transitioning periods when the outside air had low outdoor absolute humidity. Nevertheless, such low levels were encountered for limited periods. In Tokyo the RH

was lower for a higher share of the occupied time than in the other locations since the outdoor temperature was higher during the transitioning periods but the absolute humidity registered similar levels to Copenhagen and Zürich. As in Palermo the outdoor environment was both hot and humid during the winter months, it registered the least time with relative humidity levels below 25%. However, this was not a consequence of the air cleaner but of the system itself. Therefore, a more precise control of the relative humidity could be achieved by employing a humidifier or dehumidifier if needed.

Conclusion

This study showed that the total energy use for conditioning the indoor environment could be reduced by substituting part of the required air flow rate with an air cleaner. However, the amount of energy saved is in reality subject to the climatic conditions, the type of HVAC system installed, and to the additional energy use of the air cleaner itself. Nevertheless, higher energy savings are expected for low polluting buildings than very low polluting buildings when using air cleaning technology.

Although subject to the CADR and the air cleaner technology employed (Zhang, et al., 2011), gas-phase air cleaners could potentially be used in low polluting energy buildings for providing the same air quality as in very low polluting buildings while reducing the required energy use. However, high clean air delivery rates could have a negative impact on health, well-being and work productivity of occupants due to the resulting high CO₂ concentrations. Additionally, if the CO₂ concentration setpoint is not adjusted to the CADR for DCV ventilation different levels of air quality can be obtained than the ones expected.

Although no extensive humidity issues were observed with the reduction of air flow rate additional humidity control systems might be required during dry seasons or for very humid climates.

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