# Air cleaner as an alternative to increased ventilation rates in buildings: A simulation study for an office

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**Abstract:** This study analyses the feasibility of utilizing advanced air cleaner technology for air purification in a system-based filter (recirculating ventilation system), a room-based filter (local recirculation in each room), and a beam-based filter (recirculation in an active chilled beam). The results show that choosing the appropriate air cleaner can significantly impact energy performance and improvement of indoor air quality.

## Background

Air pollution poses significant risks to human health, as it comprises a combination of gaseous and particulate contaminants. Both indoor and outdoor air quality are affected by air pollution, which can either originate from indoor sources or be brought into buildings from the outdoor environment. Given that people spend most of their time indoors, exposure to air pollution primarily occurs inside buildings. This exposure has been linked to adverse effects on the immune [1], respiratory, and cardiovascular systems [2-4], as well as an increased risk of lung cancer [5] and premature mortality [3]. Short-term symptoms of exposure to poor indoor air quality include headaches, eye, nose, and throat irritation, fatigue [6], and asthma [7], which can lead to decreased productivity and increased workplace absenteeism [8].

Indoor air quality is affected by both indoor and outdoor sources [9]. Outdoor air pollutants come from different sources, such as burning fossil fuels for heating, transportation, and production of electricity, as well as waste incineration. Typical indoor sources of pollution include cleaning products, office equipment, cooking, and biological activities by humans, pets, and mould [10, 11].

To mitigate the negative impacts of outdoor-to-indoor pollution transfer, the use of supply air filters in the ventilation system improves indoor air quality. To reduce the impact of indoor pollutants, the most effective approaches are to reduce or eliminate those sources and to ventilate the space with cleaned outdoor air. An alternative technical solution to increase ventilation rates with outdoor air is to utilize filters. This can be carried out by three different methods: filtering air centrally using the HVAC system, placing air cleaners in each room [12], and utilizing a combined active chilled beam with a filter.

Studies suggest that filtration can enhance the effectiveness of source control and ventilation in enhancing indoor air quality. Installing a portable air cleaner or using the air filter in a cooker hood or using recirculation in combination with a filter in the HVAC system can be an effective strategy to reduce indoor air pollution.

Air filtration technologies need to address a range of pollutants, each requiring a different mechanism for removal or degradation. Different types of air filters have their own strengths and limitations in removing specific pollutants. This complexity can result in cumbersome and complicated multi-stage air filtration systems. The challenge of simultaneously removing both particle and gaseous pollutants necessitates a better understanding of the mechanisms involved. One potential solution is the combination of multistage devices into a single-stage air filter, an area that remains underexplored. Achieving a balance between healthy air quality, energy efficiency, and the effectiveness of the heating, ventilation, and air conditioning (HVAC) system requires careful consideration of HVAC components.

When designing filters for air cleaning, it is important to consider several criteria. One of these criteria is total building efficiency, which can be enhanced by creating filters with a lower pressure drop, reducing energy consumption while maintaining the filter's pollutant removal capacity. Another challenge is to develop filters that do not add complexity to the ventilation system. Moreover, solutions that are easy to produce, operate, and maintain while also being cost-effective should be prioritized to ensure their widespread adoption in buildings.

An HVAC system works diligently to ensure that occupants of a building are provided with the ideal thermal climate and satisfactory air quality required for their activities, compensating for any shortcomings in the building's tightness.

Two primary mechanical ventilation systems are commonly used: extract ventilation systems which rely on outdoor air supplied through wall vents and windows and balanced ventilation systems using heat recovery and filtration. Natural and hybrid ventilation systems are also used; however, traditional natural ventilation systems do not include air filtration in their design.

Approximately 35% of the energy used by commercial and residential buildings is attributed to HVAC systems [14], underscoring the significant role these systems play in the overall energy use of the building sector. Therefore, it is crucial for HVAC systems to operate at their optimal efficiency in today's context [15]. The energy use of HVAC components varies significantly based on various factors such as building type, glazing percentage, and properties, the efficiency of heat recovery, occupancy patterns, internal gains, building location, and climate. Moreover, the ventilation system design (natural or mechanical) and operation time, which can differ depending on the building type (residential or commercial) and occupancy, significantly affect the system's energy use.

Fans are responsible for air distribution and typically consume around 34% of the total energy used by ventilation systems [16]. The power required to run an HVAC fan is influenced by several system design parameters such as air flow, flow resistance, and fan efficiency. The air flow rate and fan system efficiency are determined by the system's needs, equipment selection, and building requirements, whereas flow resistance depends on component selection and ventilation system design. Air filters introduce air resistance into the system, and their contribution to the total system pressure drop can range from 20% to 50%, depending on the loading conditions, filter efficiency, and system configuration [17].

Providing a comfortable indoor climate requires technical installations that consume a considerable amount of energy. To reduce energy demand and maintain an optimal indoor environment, new solutions based on the needs and activities of occupants must be developed. The objective of this study is to investigate the feasibility of utilizing advanced air purification technology in combination with different ventilation strategies to improve indoor air quality and optimize energy use. The study aims to evaluate the benefits and drawbacks of these alternative system solutions.

## Building model

The building model was chosen to be representative of a typical office room located on the middle floor of a high-rise building. The room has a heated area of 16 m² and a volume of 48 m³. All the surfaces are considered adiabatic (thermally isolated), except for the south-oriented façade (wall), where ambient boundary conditions are applied. This facade also includes a window of 6 m². The facade has two parts, an opaque element, and a glass element, with U-values of 0.3 W/m²K and 1.5 W/m²K, respectively. Shading devices are installed outside the window, which can block 50% of incoming radiation when direct solar radiation on the south facade is higher than 150 W/m². Shadings from nearby obstacles are not considered.

Hourly resolution profiles for occupancy, appliances, and lighting were used to represent user behaviour and internal heat gains. The profiles were generated based on different user behaviours for weekdays and weekends. The peak heat gain was assumed during working hours on weekdays and was set 20 W/m². The natural infiltration rate was assumed to be constant and the air change per hour was set to 0.2 ACH.

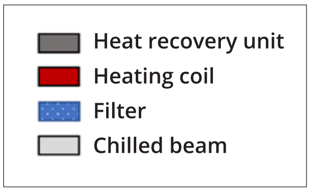
The filter was modelled to reduce the concentration of pollutants by 80%, with $CO_2$ being used as the primary pollutant. During working hours, an indoor production of 9.1E-6 kg/s of $CO_2$ was assumed, while an outdoor concentration of 400 ppm was used as a reference concentration.

An ideal space heating and cooling system was modelled in order to keep the indoor air temperature within the range of 20-24°C equal for all systems simulated.

## System models

Four different HVAC system configurations were implemented, namely: 1) Reference case, 2) System-based filter, 3) Room-based filter, and 4) Beam-based filter.

The reference case (**Figure 1**) represents a typical office ventilation system consisting of a heat recovery unit, a heating coil, and supply and return fans. The heat recovery unit was modelled as a rotary heat exchanger where the speed of rotations (effectiveness) was regulated according to the actual needs in terms of heat transfer between supply and return air streams. The maximum effectiveness was set to 0.8. An outdoor air flow rate of 20 ℓ/s is delivered to the office room by the supply fan. The office room receives an outdoor air flow rate of 20 ℓ/s from the supply fan, which has an efficiency of 0.6. The ducts were set to have pressure drops of 150 Pa, whereas the heat recovery unit was set to have a pressure drop of 200 Pa. The heating coil, which maintains the supply air temperature at 20°C, was assumed to have a pressure drop of 50 Pa.



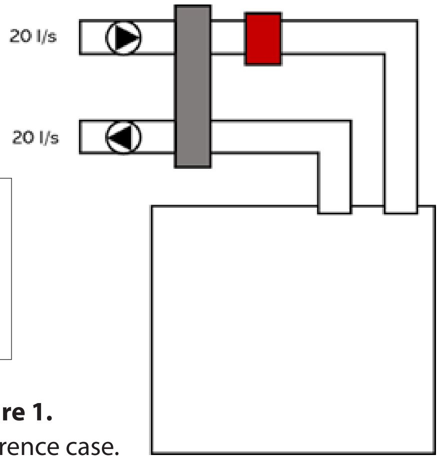




**Figure 1.** Reference case.

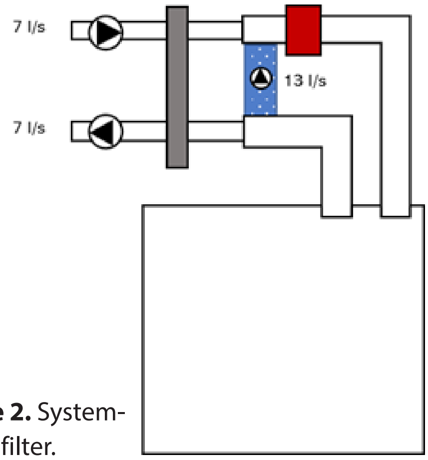
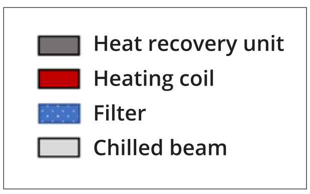



**Figure 2.** System-based filter.



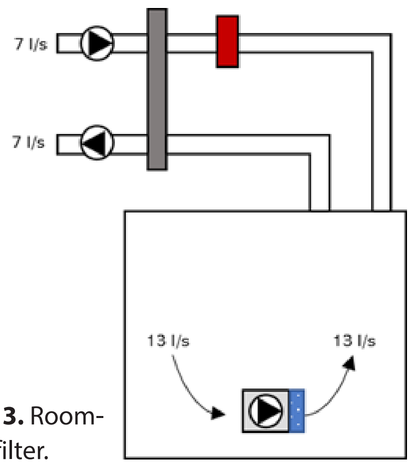




**Figure 3.** Room-based filter.

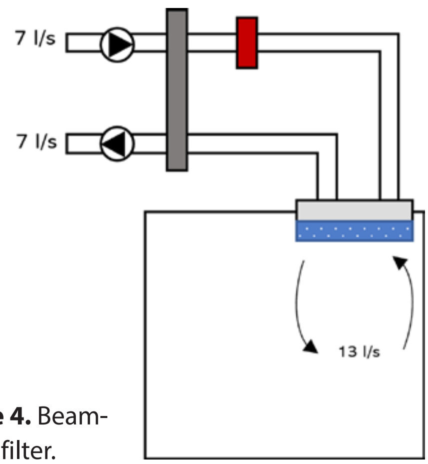



**Figure 4.** Beam-based filter.

The case "system-based filter", as shown in **Figure 2**, introduces a filter at the system level. This allows for lower outdoor air flow rates by filtering return air from the room. For this case, an outdoor air flow of 7 ℓ/s was assumed, with a 50 Pa pressure drop set for the filter. It's worth noting that this approach allows for smaller ducts to be installed in correspondence to the heat recovery unit. The filter was modelled accordingly.

The case "room-based filter" introduces a filter at room level, as illustrated in **Figure 3**. In this case, the air is filtered within the room using a small fan. It's worth noting that, such fans are generally less efficient, with a typical value of 0.25 assumed in this study. A pressure drop of 50 Pa was set for the filter.

The case "beam-based filter" introduces a filter incorporated into a chilled beam unit, as shown in **Figure 4**. In this case, the induced room air is filtered by a device integrated into the beam unit. To induce air through the beam unit, the pressure drop in the duct system was increased to 210 Pa.

## Results and discussion

A previous study [18] explored the combination of active chilled beams (ACBs) and air cleaning technologies to improve indoor air quality in offices. The researchers conducted laboratory experiments to test the effectiveness of a low-pressure mechanical filter in removing particles from the air in combination with ACBs. The results showed that the combined system was effective in removing both large and small particles from the air, resulting in improved indoor air quality. The study suggests that the combination of ACBs and air-cleaning technologies can be an effective strategy for improving indoor climate in offices. Furthermore, the measurement results of the combined system showed that adding the filter accelerated the removal rate of the particles by 2 $h^{-1}$. However, the efficiency of the chilled beam in exchanging heat was reduced by 38% when the pressure loss was less than 5 Pa.

It should be noted that the reduction in efficiency depends on a lower induction rate in the chilled beam. In the above-mentioned study [19], the induction rate is reduced from approximately 3 to 2. In the present study, the induction rate is less than 2. It means that the size of the chilled beam must be larger when installing a filter to keep the same cooling power.

### *Energy demand*

**Figure 5** shows the annual cumulative energy use for space heating in the four system configurations. The profiles are remarkably similar for the cases room-based filter and beam-based filter. The highest energy demand 23.8 kWh/m² were observed in the reference case. This is attributed to the lack of air recirculation in the reference case, resulting in lower indoor air temperatures compared to the other cases.

**Figure 6** shows the annual cumulative energy use for space cooling. The highest energy use was observed in the cases room-based filter and beam-based filter, with their profiles being almost identical. Conversely, the lowest energy demand was observed in the reference case. This can be attributed to the higher amount of outdoor air being supplied to the room in the reference case, thereby increasing the potential for free cooling during the summer months.

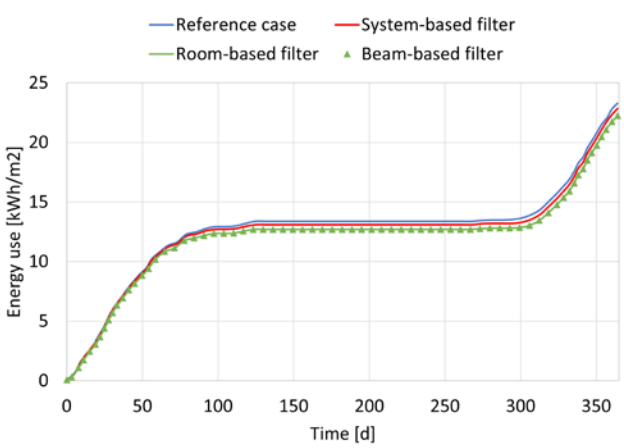



**Figure 5.** annual cumulative energy use for space heating.

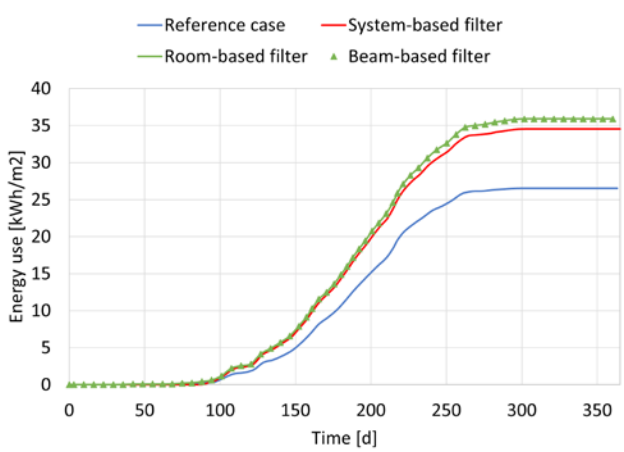



**Figure 6.** annual cumulative energy use for space cooling.

**Figure 7** shows the annual cumulative energy demand for the heating coil. The highest energy demand was observed for the reference case (24.3 kWh/m²), whereas the lowest energy demand was observed for the system-based filter (5.8 kWh/m²). This can be attributed to the higher amount of outdoor air being supplied to the room in the reference case.

**Figure 8** shows the annual cumulative electricity energy demand for fans. The highest energy demand values were observed for the reference case (13.7 kWh/m²), while the lowest values were observed for the beam-based filter (5.2 kWh/m²). This is attributed to the recirculation of air that occurred through induction in the beam-based filter case, which is more efficient than using a fan in the room (as in the room-based filter case).

**Figure 9** shows the total primary energy use for the four cases. A factor of 0.8 was used to convert space heating and heating coil energy use to primary energy use (assuming district heating or boiler as heat source). For electricity, a factor of 2.5 was used. It was assumed that space cooling was provided by a chiller with a seasonal coefficient of performance (COP) of 2.5. It can be noticed that the integration of a filter in the beam unit resulted in primary energy savings of approximately 26% in comparison to the reference case, as observed in the figure.

## *Indoor $CO_2$ concentration*

In the present study, the concentration of indoor $CO_2$ is used as a measure of overall indoor air quality.

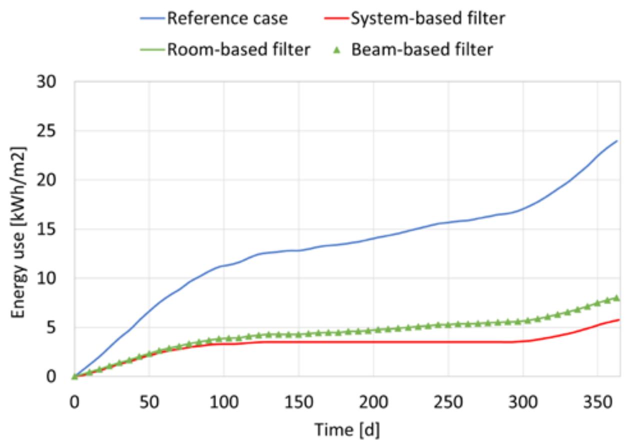



**Figure 7.** annual cumulative energy use for the heating coil.

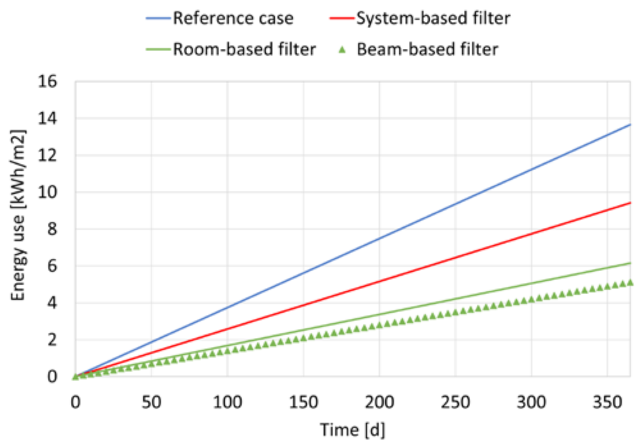



**Figure 8.** annual cumulative electric energy use for fans.

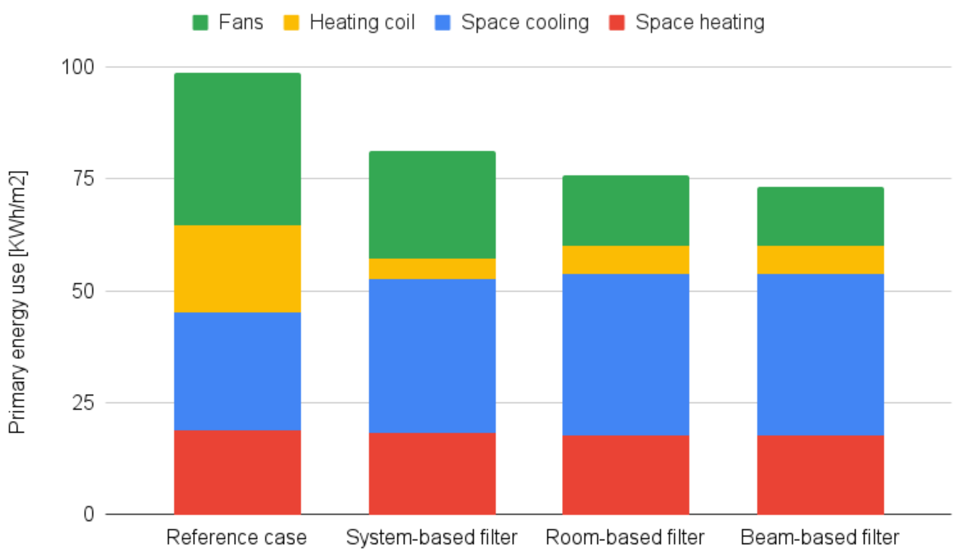



**Figure 9.** Annual primary energy use for the four cases.

**Figure 10** shows the $CO_2$ concentration during a typical day for the reference case (no filter) and for all three cases with integrated filter (with filter). The graph shows that the integration of a filter reduces the $CO_2$ concentration in the room to approximately 160 ppm during unoccupied hours and to approximately 450 ppm during occupied hours. This is a significant reduction in comparison to the reference case, indicating that the use of filters can have a positive impact on indoor air quality.

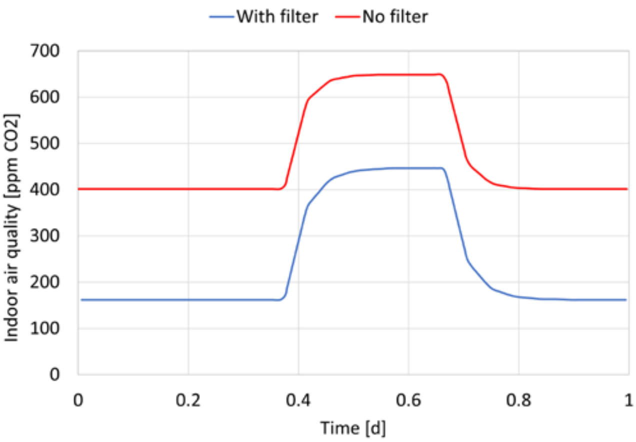



**Figure 10.** The $CO_2$ concentration during a typical day for the reference case (no filter) and for the cases that integrate a filter (with filter).

## Conclusions

Indoor air pollution can be effectively mitigated through air cleaning. Portable air cleaners or combined chilled beams with air cleaners are viable solutions for removing pollutants and enhancing the air quality in a specific room. One important question is how the placement of an air cleaner affects its ability to improve indoor air quality.

Overall conclusion:

- The study highlights the importance of considering energy performance when selecting air cleaners and ventilation systems for indoor climates.
- These findings suggest that choosing the appropriate air cleaner and ventilation system can significantly impact the overall energy performance and improvement of indoor air quality.

The results suggest that:

- The room-based and beam-based filter systems have similar energy demands for space heating, while the reference case has a slightly higher energy demand due to the lack of air recirculation.
- For space cooling, the room-based and beam-based filter systems have the highest energy demand, while the reference case has the lowest energy demand due to a higher supply of outdoor air.
- The system using filters has the lowest energy demand for the heating coil, whereas the reference case has the highest demand.
- For fans, the beam-based filter has the lowest energy demand due to efficient recirculation of air through induction, while the reference case has the highest due to higher air flow through the air handling unit.
- Integrating a filter in the active chilled beam unit results in primary energy savings of approximately 26% compared to the reference case. ■

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